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A REVIEW OF APPROACH AND LANDING GUIDANCE IN RELATION TO CIVIL AND MILITARY OPERATIONAL REQUIREMENTS

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SUMMARY

The Report summarises the provisional Civil and Military operational requirements and examines the performance and problems of microwave guidance systems in relation to them.

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CONTENTS

1 INTRODUCTION

This Report reviews trends and developments in aircraft guidance and the likely long term effect on aircraft instrumentation and operations. Several organisations are engaged in the formulation of operational requirements suited to the foreseeable needs of Civil and Military Aviation and there has been considerable effort devoted to the development of a variety of techniques applied to guidance using microwaves. These requirements, and the solutions that have been conceived, constitute a complex technical, commercial and political pattern which is probably confusing to many people in aviation. It is not appropriate to deal with the political aspects in a report such as this but it is hoped that by tabulating and rationalizing the available facts the solution of problems associated with policy making will be helped.

2 THE SPECTRUM OF REQUIREMENTS*

2.1 Present day Civil

The prime requirement in Civil Aviation at the present day is for approach and landing guidance to enable Conventional Take-off and Landing (CTOL) aircraft to operate into international and national airports. Because of the increase in size, weight and landing speed of modern aircraft the tendency has been for runways to be widened and lengthened. The main runways at the major airfields vary in width from 150-300 feet and in length from 6000-12000 feet.

2.2 The operational objectives are defined by ICAO documents[1] and these are combined with descriptions of systems and performance specifications which define internationally agreed standards. It is important to emphasise that each operational objective determines the minimum performance of many services such as airfield lighting, communications, meteorological measuring and reporting, Air Traffic Control as well as the navigational aids. In addition several environmental factors concerned with obstruction limits, airport design and administration are also regulated since they are closely concerned in determining operational limitations. For the purpose of this Report we will consider only the non-visual approach and landing aids with minor digressions where interactions with other systems make this necessary.

2.3 The operational objectives as defined by ICAO are therefore:-

Operational performance Category I: Operation down to 60 metres (200 feet) decision height and with a runway visual range not less than a value of the order of 800 metres (2600 feet) with a high probability of approach success.

*Operational Requirements are nearly always written in a legalistic style and the opportunity is taken here to extract the significant factors from each and present them in a comparable way (see Appendix A).

Operational performance Category II: Similarly worded but down to 30 metres (100 feet) decision height and RVR not less than 400 metres (1300 feet).

Operational performance Category IIIA: Operation with no decision height limitation to and along the surface of the runway with external visual reference during the final phase of the landing and with a RVR not less than a value of the order of 200 metres (700 feet).

Operational performance Category IIIB: Operation with no decision height limitation to and along the surface of the runway without reliance on external visual reference; and subsequently, taxiing with external visual reference in a visibility corresponding to a runway visual range not less than a value of the order of 50 metres (150 feet).

Operational performance Category IIIC: Operation with no decision height limitation to and along the surface of the runway and taxiways without reliance on external visual reference.

2.4 These objectives, as stated, determine the specifications for ground and airborne equipment. In addition it is assumed that aircraft and airlines are certificated in relation to their performance capabilities, avionics system design, aircrew training and procedures. Although one might argue against the desirability of discrete steps in the classification of low weather minima operations these definitions do in practice provide reasonable criteria from which the performance characteristics of equipment for all present and future aircraft operations can be deduced. However although ILS is classified as Category II or III etc., the operational capability of an aircraft depends critically on its performance characteristics. Therefore it is quite possible to envisage an aircraft certificated to say Category IIIA limits in conjunction with an ICAO Category II ILS.

3 THE NEW OPERATIONAL REQUIREMENTS

3.1 The need for a new guidance system to supplement or replace VHF ILS arises mainly from the following considerations:-

(a) The VHF system is vulnerable to interference and this may become a problem in All Weather Operations due to the restriction of traffic movements that must be imposed to maintain safety.

(b) There are siting difficulties associated with the VHF system which could be overcome by microwave systems.

(c) The operational requirements stated as necessary for the future development of aviation cannot be met in full by the VHF system.

3.2 In Appendix A the Civil and Military requirements are reviewed and a summary of the most significant aspects are given in section A.5.4.1. A pictorial summary of the provisional ICAO requirement is given in Fig.5 and the total envelope of the Civil and Military requirements in Fig.6. The most important feature common to all the ORs is the change of emphasis from 'guidance' to 'position measurement'. This means that the system being considered must consist of azimuth, elevation and distance measuring subsystems. The justification for this arises from the desire to obtain the 'flexibility under IFR that exists in VMC'. The concept is intended to play a part in solving the terminal area traffic handling problem and cannot be divorced from other aspects of ATC design.

3.3 The extensions of function envisaged are:-

(a) High integrity landing systems for CTOL, STOL and VTOL aircraft under all environmental conditions.

(b) Straight and curved approach paths in azimuth and elevation.

(c) Control of overshoot and perhaps go-around.

(d) Angle/DME control of flare-out as an alternative to the radio altimeter method.

3.4 Each of these operations introduces design problems common to most of the possible techniques which could be offered as a solution. In the rest of this Report - and particularly in the Appendices - we shall examine some of these difficulties, which must be overcome, if satisfactory operation is to be obtained.

4 MAJOR DESIGN PROBLEMS IMPLICIT IN THE ORs

4.1 System functions

4.1.1 The most important of the new requirements is the measurement in the aircraft of its position and rate of change of position relative to prescribed linear or non-linear three dimensional paths. The reasons for wanting this have been mentioned earlier and are concerned mainly with Air Traffic Control, noise abatement and the benefits that are assumed to accrue in conditions of good visibility. If we consider, briefly, how and with what effect a pilot operates near to an airport in VMC we see that:-

(a) A minimum visibility is needed, usually about 5 miles ahead with separations of at least 500 feet vertically and 2000 feet laterally from cloud.

(b) A watch for other nearby aircraft gives a measure of collision avoidance and enables station keeping for approach sequencing in heavy traffic conditions.

(c) The ground, airfield and runways will probably be in sight to give a series of visual fixes enabling special tracks (e.g. short range beam joining or noise abatement) to be flown.

(d) The confidence with which both ATC and the pilot can operate is substantially increased.

4.1.2 The ground/air system needed to maintain the benefits of VMC operations in all weather conditions must provide services to compensate for any deficiencies with respect to the above aspects (a) to (d). These services involve both ATC and the aircraft and a great deal has been written concerning the likely trends in TMA design. A functional scheme, in line with the Alexander report[2] has been outlined by Blake[3] and it is possible to detail the airborne instrumentation more closely (see Fig.28).

4.1.3 It will be seen that within the aircraft its position must be computed from measurements of azimuth, elevation, and distance, plus the appropriate constants relating the subsystem geometry relative to the runway and its direction. The desired flight path must be stored or made available on board the aircraft and the errors and error rates computed from the measured and stored position information. If we take present day CTOL aircraft instrumentation as a starting point then it will be necessary to provide the following additional equipment.

(a) A computer to determine position and relate this to the desired track. (In the simplest case the 'computer' could be integral with the guidance receiver and used for relating the information to the simple straight line approach and landing paths used at present, in which case the stored reference would be a predetermined voltage or frequency.) A further extension would be the use of on board storage of flight profiles which could be either preset before flight or programmed in flight to ATC requirements. It is also possible that with computer aided approach sequencing (CAAS)[4] or intermittent positive control (IPC)[5] the required profile may be set or updated automatically from the ground.

(b) Display instrumentation in the cockpit will certainly need to convey situation as well as director information, since the pilot will need knowledge of the intended track and warning of demanded flight path changes. Some of the

basic work has already been carried out for VTOL guidance[6] and the suggested combined vertical and horizontal displays could be modified for STOL and CTOL use. In addition it may prove necessary to add to the display to enable the 'pilot' to assess his position relative to the nearest aircraft in the sector together with a time 'lost or gained' indication to aid station keeping.

(c) The data link becomes an inevitable requirement and it will probably need to be two way. There is clearly the need to communicate ATC instructions and situation - environment information to the cockpit. It may also be essential to transfer the air derived data back to the ground. (We have not considered the ATC monitoring problem but ground access to air data is already a trend through SSR and this might be the simplest method of expanding the monitoring capability.) The return data link may also be desirable for integrity reasons which implies redundancy and cross checking. By returning the data through the reciprocal path a cross check on accuracy can be obtained and this would enable a rapid 'fault' indication to be made available at both ends of the link.

4.1.4 From the above it will be seen that the move away from 'guidance' to 'position measuring' implies considerable changes in both ATC and aircraft instrumentation. Many of the logistic solutions are dependent on a proper evaluation of the operational desirability, feasibility, and cost effectiveness of all that is implied, and there is a considerable amount of basic operational research needed to enable correct decisions to be made. However, although VMC operations are sometimes quoted as being an 'ideal situation' it should be remembered that there is normally still considerable reliance on instruments at the low heights appropriate to approach and landing, and that VMC is in practice often an intermittent variable and has well recognised dangers (see Ref.7). An 'optimum' instrumented system could be expected to perform better and more consistently than a reliance on VFR since visual estimation of parameters would be replaced by measurement and there would be an equivalent monitoring of the situation both on the ground and in the cockpit. An important point to be considered is where the interfaces should lie between the *en route* and landing phases and this should be considered in relation to the time scale since it must be expected that medium range navigational performance will improve and eventually compete with microwave navigation. A summary of the main difference between 'guidance' and 'position measurement' is presented in Table 1.

4.2 Coverage

4.2.1 Main problem areas

If we take the overall coverage envelope contained in the ORs it will be found that there are several requirements which need consideration. These are:-

(a) Continuous azimuth, elevation, and distance measurements down to as low as 5 feet above the runway surface and along its length. A complicating factor is that many runways are in excess of 10000 feet long and not necessarily flat or level.

(b) Continuity throughout approach and overshoot within a sector of at least ±150 about the runway centre line and along its length.

(c) Coverage to ... miles (30 desired) and usable down to an angle of 1° from threshold, i.e. a height of 2000 feet at 20 n miles from touchdown. (Present ICAO requirement is 1500 feet at 20 n miles 0.75°.)

(d) Extension of coverage through 360°.

(e) Reception of signals irrespective of aircraft heading.

(f) The integrity aspects require that transitory propagation disturbances due to meteorlogical effects, aircraft or vehicle movements, works services etc., should have a negligible effect on the guidance signals.

4.2.2 Low angle coverage

There are several cases to be considered. Firstly on a long CTOL runway both the localiser and DME - if sited upwind - must illuminate the aircraft when at low height before landing and during roll out along the runway. It is essential to consider the effect on the guidance signals of interference between the direct and ground reflected rays, which will have very small angular separations during much of this phase. Secondly there is the problem of shielding by trees or buildings which may flank the transmitters and affect the azimuthal coverage at low angles. A similar problem may occur due to shadowing by aircraft in front of the transmitters. In the case of a STOL runway, for instance, aircraft may be expected to turn off and taxi within a few hundred feet of the localiser or park before take-off close to the glide path or localiser.

Lastly there is the requirement for range and elevation measurements to compute flare, which again requires undisturbed propagation near the runway surface.

4.2.3 Shadowing

Some of the difficulties associated with obtaining consistent coverage at microwaves arise from shadowing. Sommerfield[8] and Rice[9] have dealt with this theoretically in terms of propagation losses in the shadows of a diffracting knife edge or parabolic surface and various measurements of diffraction losses (see for instance Ref.10) have been reported. However in practice the physical properties of a diffracting surface bear little resemblance to the idealised models which one is forced to assume in the theory and consequently measured results often conflict with theoretical predictions.

4.2.4 Since no measurements are known which apply directly to C band operation in an airport environment a programme has started at RAE to provide some relevant information. In Appendix B the tests carried out so far are discussed and compared with theory. These experiments examined the effect of trees on signal coverage and the losses in the shadow from a taxiiing aircraft. Figs.9-20 present the results and it will be seen that the range of losses will, if present in operational situations, drastically lower signal to noise ratios and limit signal coverage. The problem will be more serious than that due to rain attenuation which has received most attention in the literature. In comparison VHF (100 Mc/s) propagation is only slightly effected and the contrast in operations may become an embarrassment.

4.2.5 Ideally the microwave systems should be operated with a direct line-of-sight path between transmitter and receiver. Achieving this will be helped by having flexibility in siting of the subsystems and by raising ground aerials as far as possible. The split siting of the localiser is feasible for many guidance techniques and can be exploited to minimise siting difficulties and allow aerial height to be gained.

4.2.6 These shadowing effects have been discussed in relation to signal losses, but an important consequence which it is intended to investigate is the accompanying degradation in accuracy of angle, phase or time measurement, relative to the general requirement for an instrumental accuracy of about 1 milliradian.

4.2.7 Fading due to ground reflection

All of the elements of a microwave guidance system will be subject to interference between the direct and ground reflected signal. The resulting 'fading' or 'scalloping' may be serious enough to cause temporary loss of signal, introduce noise on to the guidance signals either by virtue of a low

signal to noise ratio or due to beats between data rates or modulations and the fading rates, or even allow capture of one subsystem by another. The problem will affect the design of localiser and DME systems in particular and will also limit the effective lower coverage of the elevation measuring system.

4.2.8 In Appendix B the problem is analysed for STOL (2000 feet) and CTOL (12000 and 7000 feet) runways with transmitting aerial heights of 5 and 20 feet. There is a possibility of limiting the seriousness by shaping of the aerial vertical polar diagram but this will only be effective on the shorter runways. It will be noted that the coverage requirements in the ORs - (down to 5 feet above the runway, at one extreme, and up to 20 or 30° elevation at the other) produce conflicting requirements in the aerial design. Furthermore, although the problem can be somewhat eased by keeping the transmitter aerial phase centre as near the ground as possible (bearing in mind that λ is 6 cm) - there will be equally good reasons - (diffraction, shadowing) - for raising the aerial in height. One also has to take account of the requirement for 'co-siting' and 'co-existence' with VHF ILS and aircraft arrester barriers.

4.2.9 A notable difference between VHF and microwave ILS is in the properties required of the ground within the Rayleigh range. At VHF, expense is often incurred in levelling or building up the site whereas at microwaves it will prove an advantage to worsen the reflection coefficient by leaving the ground contours rough. For instance, over grass paths from transmitters straddling the runway should be less affected by ground reflection problems than in-line systems looking directly along the smooth runway surface, and will also ease the siting problems posed at some runways requiring VHF ILS co-existence.

4.2.10 <u>Effective radiated power required</u>

In all systems an extension of the required coverage will call for an increase in the mean power supplied by the transmitter to the aerial. If we take a solid angle of 60° × 10° as being reasonably representative of the major ILS requirement then the full hemispherical coverage called for in the ORs will require a mean power increase of nearly 18 dBs. This ultimate requirement should be borne in mind in system design even though the majority need may be for the smaller coverage.

4.2.11 Typical transmitter mean powers required for the (60° × 10°) coverage will be about 0.5 W at C band allowing for airborne receiver losses of some 16 dB. This means that the power generators may be either solid state devices or low power TWTs. If however an increase of 50 times is to be

provided for, then either one must use multiple transmissions from separately sectored systems or resort to higher powered travelling wave tubes. Unfortunately, although the TWT has the advantages of extreme reliability and high minimum gain, its power supply invariably has a much lower MTBF and this discrepancy increases markedly as the tube mean power is increased. From experience at RAE with TWTs it is believed that the optimum size tube lies in the 20-30 W mean power range.

4.2.12 One of the factors assumed in the power estimate was that the receiving losses would total about 16 dBs - and this is a typical figure. If we assume that no improvement in aircraft aerial gain can be hoped for without reducing the operating coverage then one should consider the possibility of employing RF gain. This is a rapidly developing area of microwave technology and already several alternatives are available. The tunnel diode amplifier is the best known and has been used with an AGC loop to provide an overload protected gain of 30 dB (two stages in cascade). Several other types of transistor are being developed and gains of 6 dB per stage can be achieved over the band 5000-5250 MHz. Any of these techniques could be used to provide say 10-20 dB of RF gain and this would enable the transmitter design to be frozen around power generators suitable for all applications. The objective could be met by stipulating that the airborne receiver conversion factor (from aerial input to first IF input) should have an overall gain of say 6 dB. The apportioning of RF gain and losses between aerial, RF amplifier, mixer and feeds could then be left to individual designers with specific applications in mind.

4.2.13 The importance of taking account of the ultimate objective is common to many aspects other than the power budget. All the basic design parameters such as accuracy, data rate, bandwidth, channelisation etc. are affected the greater the coverage demanded. If system studies are based on some intermediate specification then the development potential of the system will be compromised.

4.2.14 Choice of polarisation

A design feature which will affect the performance of these systems is the choice of polarisation. In the context of 360° coverage in azimuth and up to 90° in elevation it is obvious that plane polarisation will fail in specific sectors and with certain orientations of the aircraft. On the other hand circular or elliptical polarisation introduces extra complication into the aerial systems particularly if a fairly tight control of the circularity is required.

4.2.15 However vertical polarisation greatly reduces the possibility of ground/air polarisation nulls - except in those instances where the aircraft must overfly the ground systems. (This is mainly overshoot, take-off and some aspects of VTOL operations.) In these cases the regions of possible failure will generally be at short range so that it may be worth considering elliptical polarisation as a solution and a VP/HP ratio of 10 dBs would seem to be adequate in practice.

4.2.16 From other points of view, particularly concerned with propagation, the choice of polarisation is not so clear cut - and some of the experimental evidence (e.g. Appendix B) suggests that behaviour in practical situations is not simply related to the theory. It appears that in the most troublesome regions, for instance reflections at low grazing angles and complex diffraction, the difference in performance is not critically dependent on the plane of polarisation. Overall, therefore, it would appear that the use of a predominantly vertically polarised transmission in conjunction with vertically polarised airborne aerials represents the best solution for all the guidance functions.

5 SITING CONFIGURATIONS

5.1 With VHF ILS the preferred positions for the localiser are upwind and in-line with the runway centre line, and for the glide path, offset about 500 feet from the runway centre line and 1000 feet upwind from runway threshold. Microwave systems can comply with this geometry but may also be operated in several other configurations. The split axis azimuth system for instance may be necessary to overcome shadowing and fading problems and the 'conical' systems are suited to co-located orthogonal operation. The operational requirements make a distance measuring subsystem essential, and this may be sited with either the azimuth or elevation elements. In Appendix D the combinations of subsystem and siting geometry are discussed in relation to the main operational requirements. The sites are identified with respect to the distance measuring subsystem in positions denoted by D_1 to D_4 (see Fig.26). Navigation, approach and landing is required relative to the runway so that the subsystem position co-ordinates measured from a reference point on the runway must be known in the aircraft. In Table D1 the data required on board for each type of operation is tabulated.

5.2 It will be important to choose and standardise on a runway reference point from which to measure displacement co-ordinates. Runway threshold could be used but there would be advantages for conical systems in choosing the glide path origin.

5.3 Conical and planar guidance fields

5.3.1 The basic properties of 'planar' and conical systems are described in Appendix E and illustrated by Fig.29. The difference between the planar angles θp, ϕp and the conical angles θc, ϕc, should be noted. Both systems can be used to compute the xyz co-ordinates to determine the aircrafts position, relative to the runway. In conical systems the direction cosines are measured directly in the aircraft and can be used in algebraic equations to compute the cartesian co-ordinates of the aircraft spatial position.

5.3.2 A stated objection to conical systems has been that in an offset elevation system an aircraft coupled to a glide path of angle ϕ with respect to the runway will follow a curved flight path at low heights. This can be seen by considering the conical elevation diagram in Fig.29. The aircraft flies in a vertical plane parallel to the xz plane. The intersection of this plane with the conical surface generates a hyperbola and the extent and consequences of the departure from linearity are examined in Appendix G. Similarly with planar systems curvature of the glide path will occur during approaches involving curved azimuth paths. An important factor that should be taken into account when comparing planar and conical elevation systems is the location of their origins with respect to the runway. It can be seen from Figs.31 and 32 that if threshold crossing height is taken as the parameter to standardise, the conical systems should be located nearer to runway threshold than planar systems. The difference is small - and will usually be about 200 feet, but results in a considerable reduction in the apparent discrepancy between the glide paths generated by both systems.

5.2.3 It can be seen from Appendix G that for manual CTOL operations the height difference resulting from using planar or conical glide paths is not significant. However neither system can be matched to the flare profile so that for automatic landing it is necessary to measure height above the runway either by means of a radio altimeter or by a special elevation subsystem combined with a distance measurement. Furthermore it must be remembered that without DME to enable programmed softening to the sensitivity characteristic it is unlikely that any glide path system could be flown on instruments much below 50 feet even if this was thought to be a desirable objective.

5.3.4 For higher glide path angles (STOL operations for instance) the planar/conical differences would increase if the array length and offset distance remained the same as for the 3° case. However it is likely that STOL elevation

systems will be smaller than CTOL and sited closer to the runway so reducing the differential correspondingly. A further objection that has been stated is that the hyperbolic path introduces azimuth/pitch coupling. However this also appears to be of small significance, particularly for the lower glide path angles. At 50 feet height for instance an aircraft would need to deviate 25 feet in azimuth to introduce a 1 milliradian change in glide path angle - an amount that is less than present beam bend and alignment tolerances.

5.3.5 It will be noted that for programming non-linear descent paths and flare profiles the controlling parameter should be height and its rate of change. Therefore it would seem that the whole of the descent, including the glide path phase, could with advantage be controlled by height rather than transferring between linear and angular data at different stages in the operation. From consideration of the overall objective and from the discussion in Appendix E it appears that conical systems, properly used to measure cartesian co-ordinates, are better suited than planar systems to providing all the services that are foreseen. For the simpler applications of the guidance systems, which will of necessity rely on manual control of the aircraft, either conical or planar angular information can be used with minor advantages and disadvantages associated with each.

5.3.6 General equations to derive x, y and z are given in Appendix E and although approximations can be made in some stages of the operations it seems doubtful if they have much practical value. If mixed planar/conical ground systems are used then there seems to be no alternative to providing separate computer programmes or data conversion facilities in the aircraft.

5.3.7 It will be noted that the elevation guidance asked for in the ORs is required over the whole sector in which azimuth guidance is provided. This factor will again influence the choice of co-ordinate system and the following reasons can be advanced for preferring a conical elevation system. In the first place some aircraft will require to couple in azimuth and elevation using angular data. With a conical system this elevation angle remains correct with respect to the origin irrespective of azimuth angle. A planar glide path will however introduce serious height errors at large azimuth angles; for instance at $\theta = 60^{\circ}$ the height on a planar glide path will be half that in comparison with the true angle given by a conical system and this - even though pilots may be aware of the discrepancy - will be serious from the safety point of view. The second factor connected with this is that for offset azimuth angles the

effective planar glide path angle is lowered and therefore will be more susceptible to multipath interference. This degradation will at most airfields be greater than that at the same angle along the extended runway centre line. One would expect therefore that the quality of a given conical glide path will be better than that given by the planar system used in the same manner.

6 OPERATIONAL ASPECTS OF AZIMUTH COVERAGE

6.1 It has been pointed out that one area of uncertainty is concerned with the azimuth coverage. On the one hand we have ORs which ask for 360° - and on the other the practical limitations of some of the microwave solutions has resulted in the requirements being restricted to between one half and a third of this. The following points are relevant to the argument and should be considered in the context of priorities. As will be seen, Military and Civil requirements could be substantially different.

6.2 Approach and landing

From a purely performance point of view all aircraft whether STOL, CTOL or VTOL need only a small funnel within which to beam join, approach and land on either a runway or pad. An acceptable lower limit to this funnel would be $\pm 20^{\circ}$ about the approach path. The need for increasing azimuth coverage beyond this must rest on the desirability and priority of additional operational needs. The following notes illustrate the factors involved.

6.3 Overshoot

The requirement for guidance during an overshoot of the runway poses some severe technical problems. In addition it raises the issue of 'go around' guidance which appears to be of more concern to Military than Civil Aviation and would of course demand all-round coverage in the localiser and the airborne aerials. Other methods of generating overshoot coverage have been suggested. These are to make the upwind localiser radiate to the rear in a limited sector or alternatively to use the coverage from the reciprocal localiser if provided or a specially located overshoot subsystem. It is clear that all the possibilities have difficulties or disadvantages. The 'all-round looking' solution poses aerial problems - and depending on its location, requires either high DME accuracy or high data rates. The simplest solution is to provide limited rearward coverage but this will produce a 'hole' at overfly, and require rear and forward looking aircraft aerials with maybe separate receiving systems and associated automatic switching. The use of the reciprocal localiser needs

careful investigation since the risk of jamming a landing aircraft on a normal approach could be unacceptably high. (Note: it is a requirement to switch off the reciprocal VHF localiser for all Category II and III runways.) This problem could be avoided by the use of an ancilliary relay system - sited near the runway mid point. In addition this extra subsystem would provide better coverage along the runway and avoid the hole at overfly of the rearward looking upwind localiser.

6.4 STOL-VTOL

These aircraft are capable of being operated with short final landing paths preceded by complex approach paths close to the airport. Clearly the more restricted the coverage of the guidance system the less it can contribute to these operations. In fact if flexible STOL traffic handling is required in the vicinity of the airfield then a 360° coverage maybe considered essential to accommodate the likely approach directions and give reasonable operating times under control. At the same time a long range of operation is not essential and could be limited to about 10 n miles radius. From an examination of the coverages shown in Figs.5 and 6, corresponding to the provisional ICAO OR and the overall envelope of ORs it can be seen that either could sustain operations by all classes of aircraft but that the ICAO OR will restrict the scope of STOL and VTOL operations particularly if steep descents and complex ATC approach and landing paths are found to be necessary.

6.5 Military-Civil

There are significant differences in the Military and Civil requirements which have a bearing on the coverage requirements. In Civil Aviation the operations are designed to provide regularity with a high level of safety. At a Civil airport the ATC procedures are well standardised and the main problems are handling the traffic without undue delay and helping with noise abatement. For many Military applications noise is not important, approach sectors may be conditioned by proximity to enemy territory or by the flight duration of the aircraft and under some conditions the ATC facilities maybe minimal. This has given rise in some Military requirements for the guidance system to give positive control, identification and position information on the ground for ATC in the total airspace surrounding the airfield. This together with the operational limitations that will affect STOL and VTOL aircraft if coverage is limited suggests that even some of the simplest equipments will need to provide coverage through 360° in azimuth. It is important that this be recognised as a real

requirement, if in fact it is, since some fundamental system design parameters such as data rate and the power budget are dependent on the decision and could not be changed easily at a later date if an inadequate choice is made.

6.6 A further point with regard to Civil-Military systems is the compatibility requirement which is used as an argument for a common system. The first point to note is that this is purely a Military requirement - there is no reason or desire on the part of Civil Aviation to be compatible with Military Aviation. Secondly the only system the Military need to be compatible with for many years is the VHF ILS since this will remain, particularly outside the USA, the predominantly fitted system at Civil airfields. Lastly it does not seem to make good sense to use civil ILS in a tactical or battlefield role; the increased risk of interception and destruction would seem to outweigh any advantages that commonality may have. These points do not bear directly on coverage and operational requirements but they do suggest that no great merit should be attached to a 'common OR' and that there will be no serious penalty if in fact separate Military-Civil systems are implemented in the future.

7 ACCURACY

7.1 The accuracy requirements are discussed in Appendix F and are based very much on knowledge of aircraft performance in relation to the VHF ILS specifications (Appendix A). A distinction must be drawn between three types of accuracy which will require to be evaluated.

(1) Instrumental accuracy of ground equipments used in conjunction with representative airborne equipment. This gives a figure for the sd of instrumental error.

(2) The effect of propagation, airborne aerial performance etc. When these are known we then have a figure for achieved accuracy of the radio systems in practice.

(3) The operational accuracy is a function of the overall ability of aircraft to fly prescribed tracks when using the radio aids. This is often the parameter most easily measured and two cases are important:-

(a) Under manual control.

(b) Under automatic control.

From figures available[11,12] it would seem that the improvement due to automatic control is at least 2:1. Typical flying errors should be ascertained at an early stage since these may be sufficiently gross to ease the position measuring accuracy required from the guidance systems.

7.2 It will be seen in Appendix F that some aspects of offset guidance and the angle/DME flare guidance require a high accuracy DME (i.e. 10-20 feet) and the nature of these requirements are such that they could be classed as special cases. For the great majority of aircraft and applications a 100 foot accuracy DME would be adequate - and it is questionable whether a separate system in C band is a worthwhile investment. Additionally if height measurement in the TMA based on angle/DME is to be competetive with altimeter performance an excessively high elevation accuracy will be required.

7.3 The achieved accuracy of the radio systems must be established by careful measurement and evaluation but, from theoretical studies[13] already carried out, it seems likely that the performance of the elevation subsystems will be significantly degraded a few miles from runway threshold in certain weather conditions (see Fig.34). In terms of azimuth, elevation and distance measurement in general the most variable factor influencing achieved accuracy will probably be the operational polar patterns of airborne aerials. Consideration may need to be given to restricting the required flight profiles to those which are compatible with a single nose aerial polar diagram.

8 INTEGRITY AND RELIABILITY

8.1 One of the prime reasons for developing a new landing guidance system is to overcome the integrity problems which have been met in VHF ILS. Ideally the pilot requires a guarantee that the ground systems from which he derives information are functioning correctly within a prescribed standard of performance. Similarly the airport administrator needs to know that the services he is providing have not failed or deteriorated below a set standard of performance. In addition the administrator may have the problem of maintaining a continuous service irrespective of maintenance needs or equipment failure.

8.2 A great deal has been written to show that 'integrity' can be compounded from a variety of factors to give an overall performance consistent with an acceptable accident risk. In the majority of these analyses 'pilot monitoring and intervention' have been used as essential factors in the equation. It is not intended here to quantify integrity in this way but rather to look at the engineering logic and the specific system design problems which will affect microwave guidance integrity.

8.3 A basic design

The basis of reliability in ILS lies in basic circuit design and equipment redundancy. Integrity must rely on the fundamental system design and in the

case of ILS this calls for inherent protection against multipath reflections and interfering signals plus a rigid control of accuracy. Due to limitations in technology it seems inevitable that monitors must be used on the ground and in the air to detect and correct performance variations outside of preset limits. These monitors must in turn be used in logical manner to protect against false alarm or failure to warn.

8.4 A method of achieving the performance which may be demanded at some international airport runways is shown in Fig.33. The scheme could with minor changes be adapted to most systems and is shown applied to a scanning system such as Doppler ILS.

8.5 The complete system consists of two separate installations - each operating on its own channel and capable of providing the required high integrity service on each channel. This duplication provides the means for maintenance or repair at any time without the need for closing down the service. It also provides an insurance against the occasional catastrophic fault which could shut down one channel completely. It will be noted that the duplication must include the aerial arrays and in the case of azimuth systems the co-location problem may be eased by split axis configurations.

8.6 The essential features of each system are a dual transmission from a combined array, using separate directions of sweep, coupled with integral monitoring of these scans. The integral monitors, which must be aligned to the required course zeros, can be used to both monitor the guidance parameters or provide feedback control of the individual transmitter alignments. Cross checks on the integral monitoring are provided from separate monitors fed from couplers in the transmitter feeds to the aerials. If integral monitoring proves difficult due to the aerial design then a similar arrangement can be used based on monitoring probes sited separately from the aerial. However in this case the ability to monitor effectively in the near field of scanning systems will need to be analysed since the transition to far field performance will occur some 1000-2000 feet from the aerial.

8.7 <u>Integrity problems in system design</u>

There are a number of problems which arise in the practical implementation of microwave systems that could influence the basic design concept. Some of these, due to propagation, have been discussed in some detail. The following points should also be noted and resolved before system development is undertaken.

8.8 Multiplexing

The azimuth, elevation and DME subsystems may be time multiplexed, frequency shared or operated in mixed frequency-time sharing modes. In the case of time sharing the intention would be to integrate several services into one channel. This is generally only viable if the separate channels are similarly matched in terms of bandwidth so that if narrow band azimuth-elevation systems are to be used the interrogator-transponder DME system must be separately channelised. An ideal time-frequency DME could however be time shared. For synchronisation of the sub-systems - which will often be located a substantial distance apart - it is necessary to employ either radio or cable links or a common reference clock. These links and the airborne receiver sorting circuits must be guaranteed failure free and a certain amount of cross monitoring between the ground subsystems will be essential.

8.9 In the time multiplexed receiver the agc and limiter actions need careful study. For instance in the case of a localiser separated by 2 miles from the elevation subsystem the aircraft receiver will normally be subject - in the region of runway threshold - to an elevation/azimuth signal ratio of at least 20 dB and maybe - depending on runway shape, lobing etc. - up to 40 dB. It will be essential to show that capture or blocking of the azimuth channel by the elevation transmission cannot occur under these circumstances.

8.10 It is probable that an optimum design will be based on frequency sharing of separate services reserving time multiplexing for the common subsystems (e.g. orthogonal azimuth systems cf. Appendix E). A further advantage of frequency sharing in this way lies in the fact that elevation and azimuth systems can be separately optimised and use correspondingly higher data rates.

8.11 DME performance

The proposal to use angle/DME flare guidance introduces the type of integrity problems usually associated with azimuth systems into the design of the DME, and therefore into the elevation channel. Apart from the propagation problems and the need for high accuracy there is also the question of interrogation overload from landing aircraft. The transponder will need to handle a wide dynamic range without decrease of accuracy if an aircraft is not to capture the system during landing and roll out at the expense of other aircraft within the coverage. This is another reason for suggesting that the whole flare guidance system be separated into the 15 Gc/s band for those that wish to use it.

8.12 Flare guidance

One of the reasons for advocating angle/DME flare guidance is that the undershoot profile of some runways may provide problems for radio altimeter control. However it should not be thought that the use of a DME - and second elevation subsystem will not also suffer from site effects. In particular snow accumulation and runway contours will pose problems in practice and the advantages which h ve been claimed should be viewed with caution. A further argument that has been used is that the radio altimeter is brought in late in the landing - but this is not fundamental - as is evident in some of the new flight control system designs. In both systems a transition is required and although the radio altimeter can be tested and in use throughout the approach and landing there will be many occasions when the 15 Gc/s band signals are not received until late in the approach. It should be a matter of some concern that a relatively untried and unvalidated technique should have been introduced as an operational requirement, particularly when its effect on the overall system design is so severe.

9 SUMMARY AND CONCLUSIONS

9.1 Microwave guidance is moving out of the 'operational requirement' specification stage and into the first phases of system selection and design. It has been shown that the statements of requirement need to be rigorously examined and interpreted in engineeri g terms. In particular it will be necessary to decide the limits of system complexity since these have a direct bearing on basic design param ters. The areas in which work is needed most are those concerned with TMA con rol and possible uses of the position measuring capability, the role and specification of the DME, the use of and acceptable standards for angle/DME flare guidance and system integrity related to the future operational environment.

9.2 It appears that 'distance measurement' has not been considered in the same depth as the azimuth and elevation systems. Airline operators will undoubtedly view with some concern the possibility that aircraft will be required to carry two DME equipments - one at L band for medium range navigation and one at C band for short range navigation, approach and landing. An economic study of some consequence could be the worth-to-aviation of a second DME. It must also be borne in mind that a third interrogator-transponder system - SSR - is in use and it should be questioned whether the three systems with their associated redundancy, represent the best technical or most cost-effective solution.

Associated with this class of equipment is the data-link and it would seem desirable to consider the better integration of these services in the context of the long term requirements. If the interrogator-transponder technique is discarded in favour of a one-way ranging system then consideration should be given to providing independent measurements from each of the subsystems to the aircraft since this will considerably ease the airborne computing problems.

9.3 The choice of co-ordinate system has been examined and it is concluded that conical systems - correctly used - offer the best solution particularly if the long term requirements are important. It is anticipated that aircraft, computers, storage systems, flight control systems and displays will use cartesian xyz co-ordinates and these are given directly by the conical direction cosines and DME slant range. Although mixed planar-conical systems could be operated in Civil Aviation it seems important that a single solution be agreed to avoid undue complication of airborne equipment. In order to use position measuring systems effectively thought must be given to the display of situation and director information and this may need to be supplemented by relative position information if the greatest TMA benefits are to be derived.

9.4 It is worth reiterating that the microwave system must provide high integrity guidance for all weather operations - and that achieving this level of performance will not be simple. This basic aim is in danger of being overshadowed by the more exotic requirements which have been envisaged and also by the commercial incentive that exists to provide low cost - simple systems for the major market. It would be useful to supplement the operational requirements with a technical plan outlining an agreed minimum complexity designed to guarantee the performance of major runway Category III equipment.

9.5 The ORs have been presented and even though they are provisional it is pertinent to suggest that there has not yet been sufficient 'operational evaluation' in the formulation of them. Some of the original requirements have been modified as a result of guidance system design quirks and it is possible that this has resulted in some fundamental errors. For instance it has been the tendency to couple the broadest coverages with the most demanding classes of service, yet in practice it may well transpire that the most sophisticated landing aids will require only narrow sector coverages and that the simplest small airfield, STOL and tactical systems will need 'hemispherical' coverage in order to provide a worthwhile service. In addition very little attention has been given to the flight control, display and communication implications and it should

be remembered that the effectiveness of the proposed system in a practical ATC environment will depend very greatly on obtaining the active co-operation of all aircraft.

9.6 The Report has indicated some specific problems which will need investigating. These include the effects of propagation disturbances and airborne aerial performance on accuracy and coverage. If reception through 360° of heading remains a firm requirement then the aircraft aerial problem could prove intractable. It may be more satisfactory in the long term to devise TMA and final approach procedures tailored to the performance achieved with simple forward looking aircraft aerials. Also it should be noted, in the TMA context, that the elevation system may be inherently incapable of realising the accuracy needed if angle/DME derived height is to be competitive with altimetry over a reasonable service area.

9.7 Finally, consideration should be given to how the new ICAO requirements can be implemented internationally. It is generally conceded that progress in Civil Aviation should be evolutionary, with changes being assimilated in the most cost effective way. If this is to be so then thought must be given to the problems of integration in those areas which are at the moment well served by VHF ILS.

Appendix A

THE SPECTRUM OF REQUIREMENTS SUMMARISED

A.1 It is appropriate to start the review of new operational requirements by summarising the VHF ILS specifications detailed in the official ICAO publications. In fact it will be found that the new ORs rely heavily on existing ILS performance specifications to define their own performance standards. It is a general rule that any new microwave system would be expected to maintain the quality of service appropriate to the present categories of operation.

A.1.1 The main Civil requirement for a new guidance system has been developed by the ICAO All Weather Operations Panel and it is based on the work of several national committees. In Military Aviation there has been most emphasis on tactical landing aids but this work is leading to the development of overall requirements by the NATO sub group 7. In the summary which follows it will be seen that a common pattern is emerging and that in order to find satisfactory solutions a great deal of fundamental research and development will be necessary.

A.2 ICAO ILS specification

A.2.1 The VHF instrument landing system is the internationally agreed approach and landing aid meeting the performance specification set out in Annex 10. The required minimum performance parameters have been extracted from the ICAO document and are summarised below. Three classes of facility are described related to the Category I, II and III operational objectives.

A.2.2 Basic requirements

The ILS consists of a VHF localiser, UHF glide path and VHF marker beacons. Each element has associated monitoring, remote control and indicator equipment. The remote monitoring is required to inform the ATC approach controller of the operational status of the ILS. It is stated that the localiser will be sited in line with the runway centre line and upwind. The glide path is required to be sited at a safe distance from the runway edge with the glide path origin related to the desired touchdown point and the aircraft height over runway threshold.

A.2.3 Azimuth service (localiser)

Coverage: Fig.1 summarises the requirements. Within $\pm 10^{\circ}$ of the runway centre line the coverage extends to 25 n miles; from $\pm 10^{\circ}$ out to $\pm 35^{\circ}$ to 17 n miles and if greater coverage than this is provided then it should extend to 10 n miles.

The vertical coverage is required up to 7° and down to 1000 feet (300 metres) at the distances specified above. This volumetric coverage is based on a standard aircraft aerial/receiver combination and assumes that the aircraft is heading directly towards the facility. For Category III localisers the signal strength must be at least 200 microvolts/metre at a height of 6 metres (20 feet) along the runway from the threshold to the stop end.

Quality of azimuth signals

The guidance signal to noise ratio in ILS is a function of interference between the wanted and reflected signals rather than atmospheric or man made noise. The guidance signal disturbances due to 'reflected interference' degrade the system accuracy and are referred to as 'beam bends'. The requirements related to Category I, II and III localisers are summarised in Fig.2.

Note: The guidance signals from ILS receivers are measured in microamps related to angle. In order to standardise facilities sited at runways of differing length the sensitivity of the localiser is adjusted so that full scale indication on a standard aircraft ILS meter (i.e. ±150 microamps) corresponds to a displacement of ±350 feet (±105 metres) about the centre line at runway threshold. It will be seen therefore that the relationship microamps per degree varies according to the runway threshold-localiser distance. The beam noise tolerances shown in Fig.2 are drawn to show both guidance current and angular limits related to runway length.

Course alignment accuracy

The localiser mean course line must be adjusted and maintained within the following displacement limits relative to the centre line at runway threshold:-

(a) Category I ±10.5 metres (35 feet).

(b) Category II ±4.5 metres (15 feet).

(c) Category III ±3 metres (10 feet).

These are generally interpreted as 'never to be exceeded' limits.

The airborne receiver also contributes to the system zero error. The ICAO document relates the tolerance to aircraft stall speed for Category I and II operations. The most stringent requirements for an aircraft stall speed of 110 knots are 7 microamps (1σ) for Category I and 5 microamps (1σ) Category II. In addition most administrations have minimum performance requirements for ILS receivers and the Board of Trade Category III tolerance is set at 2.5 microamps (1σ).

Displacement sensitivity

The nominal sensitivity is required to change linearly within DDM limits of ±0.18 from the course line. The mean nominal value is standardised at 1.43 microamps/metre (0.43 microamps/foot) at the runway threshold and the tolerance about this should be adjusted and maintained within limits of ±10% for Category II and III facilities.

The Board of Trade tolerance for airborne receiver sensitivity is 5% (Category III).

A.2.4 Vertical service (glide path)

Coverage

The glide path angle (ϕ) should be adjustable from 2 to 4° with respect to the horizontal with an operationally preferred value of 2.5°. The azimuth coverage (Fig.3) is required to be ±8° minimum with respect to the runway centre line to a distance of 10 n miles.

The vertical coverage is required up to 1.75ϕ and down to 0.45ϕ above the horizontal. This volumetric coverage assumes that the aircraft is heading directly towards the facility.

Quality of vertical signals

The requirements for Category I, II and III services are shown in Fig.4. Since the glide path siting can be fairly well standardised, the quality has been related to both microamps and angular error at the preferred glide path angle.

Note: The position of the glide path origin should be a function of the actual glide path angle chosen. This is because a reference datum is defined for all facilities such that the mean glide path should cross the runway threshold at a height of 50 feet (15 metres) with a tolerance of +3 metres (10 feet) for Category II and III or ±3 metres for Category I operations.

Glide path alignment accuracy

The glide path must be adjusted and maintained within the following angular limits relative to the nominal glide path.

(a) Category I and II ±0.075ϕ from ϕ (approximately 0.18°).

(b) Category III ±0.04ϕ from ϕ (approximately 0.1°).

The recommended glide path receiver centering tolerances (1σ) are 12 microamps for Category I and 9 microamps for Category II. The Board of Trade Category III tolerance is set at 5 microamps (1σ).

Displacement sensitivity

The displacement sensitivity is required to be as symmetrical as possible above and below the glide path. For Category I performance a control signal of 75 microamps should be achieved with a tolerance of $\pm 0.02\phi$ at an angular displacement below the glide path of 0.12ϕ and the sensitivity adjusted and maintained within ±20% of nominal. For Category II performance 75 microamps should be achieved with a tolerance of $\pm 0.02\phi$ at 0.12ϕ below the glide path and with a tolerance of $+0.12\phi$ and -0.05ϕ at 0.12ϕ above the glide path. For Category III performance 75 microamps should be achieved with a tolerance of $\pm 0.02\phi$ at angular displacements of 0.12ϕ above and below the glide path.

The Board of Trade tolerance for airborne receiver sensitivity is 10% (Category III).

A.2.5 Distance measurement (markers)

Normally an outer marker and a middle marker beacon are used to indicate distance from threshold but provision is also made for an inner marker to be used if required. The following table summarises the main performance requirements.

	Siting	Coverage	Coding
Inner	300-450 metres from threshold and within ±30 metres of extended runway centre line.	Duration of visual signal in cockpit 3 seconds ±1 second aircraft speed 96 knots.	3000 Hz tone keyed at 6 dots per second.
Middle	1050 metres ±150 metres from threshold and within ±75 metres of extended runway centre line.	Ditto but 6 seconds ±2 seconds.	1300 Hz tone keyed dot and dash alternately. Dots at 6 per second, dashes at 2 per second.
Outer	3.9 n miles nominally but within 3.5 and 5 n miles from threshold.	Ditto but 12 seconds ±4 seconds.	400 Hz tone keyed at 2 dashes per second.

A.2.6 System reliability

A high probability of performance within specified limits has to be assured consistent with the category of operational performance concerned. For Category III performance it is suggested the separate subsystems should achieve an MTBF of 4000 hours.

A.2.7 Continuity of service

A restriction is placed on the time during which guidance signals outside the system tolerances can be radiated. These are (a) 10 seconds for Category I localisers and 6 seconds for glide path, (b) 5 seconds for Category II localisers and 2 seconds for Category II glide path and (c) 2 seconds for Category III localisers and glide paths. These times include time to detect a fault, change over to a new system and monitor the new service. In the event of failure to achieve a new service within these periods it is intended that at least 20 seconds should elapse before further attempts to regain service are made.

A.2.8 Identification and data link

The localiser must carry an identification of runway and approach direction consisting of a 2 or 3 letter morse code, the modulations being at 1020 Hz and keying rate approximately 7 words per minute.

Provision is also made for limited ground to air voice communication on Category I and II localisers to be operated simultaneously with the navigational signals and identification.

A.2.9 Monitoring

The monitoring must provide a warning to appropriate control points of any malfunction and should cause one of the following actions to be carried out:-

(a) transmission to cease,

(b) removal of navigational and identification signals from radiated carrier,

or (c) reversion to a lower category of performance in the case of Category II and III facilities.

A.2.10 General comments

The above requirement has been compiled from the official ICAO documents. However in the case of the VHF ILS the 'system' preceded the 'OR' to some extent so that the official publications contain a great deal of additional

information related to technical features and quirks of the VHF system. It is probable that any future OR will need to be revised and rewritten to legislate for the specific peculiarities of the system chosen to satisfy its requirements. The history associated with developing the ICAO documents provides a useful guide to the time, money and effort required in establishing a working international standard.

A.3 Future Civil operational requirements

It is envisaged that the growth of aviation in the last quarter of this century will force an extension to the operational capabilities of the existing ICAO ILS, and it is generally assumed that a new approach and landing guidance system using microwave technology will be the most satisfactory means of designing for the performance demanded.

The first real attempt to generate an OR was carried out by the RTCA in 1968. In the UK the Board of Trade also produced ORs covering each of the classes of operation that could be foreseen. These activities have been added to by inputs from other ICAO members so that recently (1970) a provisional requirement has been generated and this is likely to be adopted as the basis of an agreed ICAO document.

To be complete one should tabulate each of the ORs but this is an unnecessary complication. As can be imagined the ICAO version is already a hybrid of the various inputs so that there is a substantial amount of common ground. We will therefore summarise the New Civil requirements by using the ICAO OR as the basis. Any significant differences between this and the other known versions will be appended to enable a complete picture to be seen.

A.3.1 Operational requirement for a new non-visual precision approach and landing guidance system for Civil Aviation[14]

A.3.1.1 General

The requirement is for a precision, high integrity approach and landing and overshoot guidance system suitable for deployment at most aerodromes and runways without restricting movement rates and without itself being restricted by weather or siting conditions. The requirement is also for system flexibility to permit visual approach procedures to be used in all weather conditions and to provide compatible simplified systems for more modest operations.

The system is required to be used by any envisaged CTOL and STOL aircraft and capable of limited VTOL operations. It will provide azimuth, elevation and

distance information during the approach and landing phase. In addition azimuth and distance information is required during the roll out phase or during an overshoot.

The guidance information must enable the aircraft to follow straight or curved linear three dimensional paths within the volume of coverage. It is envisaged that an airborne computer will be essential to fully exploit the systems potential.

The system must not conflict with the requirements of ICAO Annex 12 or other related documents and must coexist without causing interference to any other ICAO standard navigation or communication system. It should assist ATC in achieving the maximum possible movement rate, and provide guidance information to all aircraft (maybe up to 200) expected to use the service simultaneously, consistent with an accident risk of 10^{-7}.

A.3.1.2 Azimuth guidance

Coverage

The following defines the minimum limits within which lateral position information is required (see also Fig.5). It covers the requirements of approach, roll out and overshoot.

(a) Approach

At least $\pm 40^{\circ}$ about the extended runway centre line to at least 20 n miles and preferably 30 n miles and throughout the vertical coverage in which elevation guidance is given.

(b) Roll out

± 150 feet (45 metres) about runway centre line from runway threshold to the stop end and extending vertically between 5 and 150 feet above the runway surface.

(c) Overshoot

± 150 feet (45 metres) about the runway centre line (plus clearance signals beyond this) up to a height of 2000 feet over the runway. Beyond the runway stop end $\pm 20^{\circ}$ about the runway centre line extended to a range of 5 n miles and a height of 5000 feet.

A.3.1.3 Vertical guidance during approach and landing

Coverage

The minimum coverage is shown in Fig.5. Vertical position information is required throughout the azimuth systems coverage (i.e. at least $\pm 40^{\circ}$ with respect to the centre line) and in vertical sectors from near the runway surface to 150 feet height for flare guidance and in an angular sector from the obstacle clearance surface to 15° (30° desired) from touchdown above the horizontal up to a height of 20000 feet.

A.3.1.4 Distance measurement

Coverage

Distance information is required throughout the volume in which azimuth and vertical position measurement is provided.

A.3.1.5 Range of aircraft speeds and altitudes

(a) Speeds up to 200 knots.

(b) Bank angles up to 40°.

(c) Pitch angles 10° nose down - 25° nose up.

(d) Aircraft heading through 360° within service area.

A.3.1.6 Accuracy and quality of guidance

The accuracy and quality of the guidance information must be sufficient to ensure a safe, stable and accurate approach and landing. The system must provide aircraft instruments and AFCS services at least equivalent to those provided by ICAO standard ILS.

A.3.1.7 Guidance signal deviation

In azimuth the guidance signal is required to be unambiguously proportional to deviation from any chosen angular path within the sector and to vary linearly near the runway extended centre line.

In elevation the guidance signal deviation must be linear from the lower limit up to 5° and be unambiguous throughout the coverage. The deviation functions in azimuth and elevation must be common to all system implementations.

A.3.1.8 Identification

Positive identification, within the aircraft, specific to the aerodrome and runway shall be provided.

A.3.1.9 Failure warning

Unambiguous warning of system failure must be provided both aurally and visually.

A.3.1.10 Siting

Any ground equipment should be easy to site and located within the aerodrome boundaries.

A.3.1.11 Routine flight inspection

The system performance should make routine flight inspection unnecessary.

A.4 Other Civil ORs

A.4.1 General

The ICAO provisional OR does not break the requirements down according to the category of operation or class of aircraft. It is intended that compatible variants will coexist within the broad definition of overall requirement. Two inputs to the ICAO working group were ORs from the USA and the UK. It is sufficient to list any significant differences between them and the ICAO paper.

A.4.2 UK draft ORs for a non-visual guidance for approach and landing, Parts I, II and III

A.4.2.1 Description

The documents separated the requirements into:-

Part I : System suitable for Category I, II and III CTOL operations at major airports.

Part II : A less costly basic system for Category I CTOL operations at small airfields and subsidiary runways.

Part III (A and B): A system suitable for other aircraft such as (A) STOL, (B) VTOL.

A.4.2.2 Significant differences between the overall UK and ICAO provisional ORs

(1) Coverage

The approach coverage requirements were limited to minimum figures of $\pm 20^{\circ}$ in azimuth, between 1° and 20° in elevation (up to 10000 feet maximum) and 15 n miles in range for the azimuth guidance, and similarly but to 10 n miles for elevation guidance, for all classes of CTOL and STOL. For VTOL the azimuth and elevation guidance coverage required is 360° to a range of 5 n miles from

the landing area and to a height of 5000 feet. At the landing area guidance is required down to ground level and at a height of 1000 feet above the landing area at maximum range.

(2) Range of aircraft attitudes and parameters

For CTOL and STOL: 30° roll and $\pm 15^{\circ}$ pitch - any heading. For VTOL 30° roll and $\pm 20^{\circ}$ pitch any aircraft heading, and airspeeds from 0-300 knots.

(3) Elevation guidance for flare and VTOL operations

If the vertical guidance is to be used for flare the coverage is needed down to 5 feet above the runway surface consistent with the furthest touchdown point envisaged, otherwise vertical guidance need not be provided at a distance less than 500 feet from touchdown. For VTOL elevation guidance is required up to 90° above the horizontal.

(4) Distance information

For CTOL-STOL distance information is required for distance from threshold during approach and distance during roll out and it is not required to be an integral part of the system. For VTOL it is required to be integral and to be used for position measurement.

(5) Overshoot guidance

It may be desirable to provide sufficient vertical guidance, in addition to the azimuth guidance, to indicate a minimum safe climb out path.

(6) Guidance information

For CTOL and STOL the requirement is essentially for guidance information as distinct from position information.

A.4.3 Significant differences between the USA (SC117)[16] and the ICAO provisional ORs

A.4.3.1 General

The RTCA (SC117) OR was developed against criteria covering (a) airports, (b) approach and landing paths, (c) classes of service and (d) operational considerations. It covers both American Civil and American Military needs (such as tactical and portable systems) and includes limited VTOL needs.

A.4.3.2 Coverage

The most stringent requirement is for lateral and vertical position information in a sector of $\pm 90^{\circ}$ and up to elevation angles of 15°. Desirable aims are elevation to 30° and range of operation out to 30 n miles.

A.4.3.3 Overshoot and climb out guidance

Provides for an elevation guidance service in the departure zone. Azimuth coverage in departure zone same as in approach. This coupled with the ±90° approach coverage implies a maximum requirement for 360° coverage.

A.4.3.4 Obstacle warning and data channels

A service to provide obstacle clearance warning and the capability for transmitting simple data messages for visual display in the cockpit.

A.4.3.5 Omissions

There are some omissions in the SC117 OR, e.g. range of aircraft attitudes to be catered for, figures covering system capacity and reliability or integrity related to accident risk.

A.5 Military operational requirements*

A.5.1 General

ILS has not been deployed extensively by Military Aviation; greater emphasis has been placed on the use of radar, GCA or Babs-Eureka type systems. The RAF however has used a 'British Military ILS' at some airfields and this is broadly equivalent to a ICAO Category I VHF ILS. It is clear however that Military Aviation is moving into an 'ILS' era and consideration is being given in NATO to the future requirements. A first task was to develop an OR for a tactical 'portable' system and this is leading to the development of an OR covering the total future requirement.

The only known complete requirements offered for NATO consideration are those from the USA and the UK and these are summarised below.

A.5.2 USA operational requirement (SC117)

The OR of the RTCA SC117 is a joint Military/Civil OR. It has been covered under the sections dealing with Civil requirements. The following notes supplement the summaries with further points of Military significance.

A.5.2.1 General

The requirement covers simple systems capable of being hand carried to a site and rapidly set up as well as the more complex systems covered by the full requirement. Operation in arctic, tropical or jungle environment is also called for.

*At the time of writing the NATO Industrial Advisory Group has started the preparation of operational requirements covering the long term Military needs (see Addendum to Appendix A).

A.5.2.2 ECCM

The elements of the system must recognise and warn against the presence of interfering signals which would affect flight safety.

A.5.3 RAF operational requirement for long term (post 1975) instrument landing aid[17]

A.5.3.1 Overall objective

The requirement is for instrument and landing guidance systems suitable for helicopter, V/STOL, fighter, ground attack and transport aircraft. The operational airfields may be forward battlefield landing sites, tactical airfields or main base airfields and the range and weather limits to be catered for extend to operational Category IIIA. The system must provide azimuth, elevation and range measurements within a hemispherical coverage, to allow flexible approach path profiles to be flown and to supply aircraft position information for surveillance and ATC.

A.5.3.2 Coverage

Hemispherical coverage through 360° in azimuth to a range of 20 n miles line of sight (narrow sector of $\pm 20^{\circ}$ about runway extended centre line minimum acceptable for some application. Elevation guidance coverage to be hemispherical to a height of 5000 feet and line of sight range at least 5 n miles. Range measurement coverage to be hemispherical to a range of 10 n miles.

A.5.3.3 Guidance functions

(a) Straight line and curved profiles in both azimuth and elevation.

(b) Selection of flight profile to be by ground controller if required.

(c) Glide slope to be both ground and air selectable.

(d) Provision of blind transition from wingborne to jetborne flight.

(e) Overshoot and go around guidance.

(f) Take-off guidance in elevation and azimuth.

A.5.3.4 Accuracy and quality of information

Sufficient for use of either flight director or rate stabilised automatic flight control systems to Category II and III performance limits. Slant range accuracy to be 30 feet or 5% (whichever is the greater).

A.5.3.5 Capacity

Control of at least 6 and preferably 10 aircraft at once.

A.5.3.6 ATC surveillance and aircraft identification

The ground controller is to be provided with a suitable display for surveillance and the means of identifying any aircraft using the guidance system.

A.5.3.7 ECM/ECCM

The system is to be as immune as possible from interference or position fixing by the enemy. Maximum resistance to ECM is required.

A.5.4 Summary of total requirement

A.5.4.1 The various ORs combine to give a picture of the total requirement. Several important points arise:-

(1) A common feature has been the change of emphasis from 'guidance' to position measurement (i.e. essentially navigation).

(2) The widest variations are concerned with coverage requirements. It is evident that some constraints have been introduced because of limitations in the assumed solutions. Two extreme requirements are those for accurate angle measurement near the ground, along the runway and into the undershoot for flare guidance, and for 360° azimuth coverage to allow fully flexible approach, overshoot, back approach and go around guidance coupled with elevation measurement up to 90°. The overall volumetric coverage is shown in Fig.6.

(3) The major operational extensions of ILS are to (a) high integrity systems for Category III guidance, (b) STOL and VTOL guidance, (c) overshoot and go around guidance (d) flare guidance as an alternative to the radio altimeter, (e) approach path flexibility probably through the use of airborne or ground computers.

(4) There is a preference for a basic common system to cater for all classes of service and also for common Military/Civil use.

(5) The Military user may demand special ECCM characteristics and an inbuilt capability for local ATC.

A.5.4.2 These requirements raise a large number of questions associated with the design of guidance systems, the cost of ownership and operating,

aircraft instrumentation and operational procedures. In addition the overall requirement that the system must integrate with and assist Terminal Area Traffic Control raises many fundamental questions that must be answered. In other sections of this Report some of the major problems are examined.

Addendum to Appendix A

OPERATIONAL REQUIREMENTS PREPARED BY THE NIAG SUB-GROUP I

This OR has recently been completed and closely resembles the Civil and Military ORs presented in Appendix A. The following points are noted as being extensions of or differing from the ICAO provisional OR.

(a) It covers all Military CTOL-STOL and VTOL needs up to Category IIIB operations.

(b) An accident risk of less than 10^{-7} for Category IIIB main base operations.

(c) Aircraft attitudes $\pm 45^{\circ}$ roll, $\pm 20^{\circ}$ pitch.

(d) Azimuth guidance in $\pm 40^{\circ}$ but 360° for some users.

(e) Operating range 20 to 30 miles in most adverse weather conditi

(f) Vertical coverage from 1° to 15° minimum, preferably 90°.

(g) Vertical guidance through $\pm 40^{\circ}$ in azimuth but 360° desired and between the horizontal and preferably up to 90°. Provision for VTOL aircraft to make instrument transition prior to vertical landing from wing borne to jet borne flight.

(h) System shall provide distance to go and lateral guidance information throughout the flare, landing and roll out when required.

(i) Taxi guidance is desired.

(j) Overshoot guidance in azimuth is required with elevation guidance in overshoot sector desirable.

(k) Take-off guidance required in azimuth with elevation and runway distance to go desirable.

(l) Substantial immunity to interference and possibility of position fixing or counter-measures.

(m) Requirement to deploy tactically in 15 minutes or less in all weather conditions.

(n) The system should provide an output of ATC information.

(o) System to permit simultaneous guidance to two or more runways or landing sites with ability to select multiple guidance origin offsets.

(p) Distance measurement specifically through 360° of azimuth and out to 20 n miles.

Appendix B

SHADOWING

B.1 An important consideration for an ILS is the ability to fill the total coverage in which guidance is required with signals having a continuous and adequate signal to noise ratio. Physical obstacles in the path between transmitter and receiver give rise to reflection and diffraction which will produce an attenuation and, in the case of a moving receiver, fluctuation of the received signal. The effects are a function of the transmitting wavelength in relation to the obstacle size so that one method of reducing the problems encountered with a VHF ILS would be to move to a longer wavelength (say to LF or VLF) where nearly all obstacles would be small in relation to the wavelength. However for a variety of reasons it is proposed to move up in frequency to microwaves (5000 or 15000 Mc/s). It is important to realise that by doing this the basic propagation problems are all worsened. The improvements to be gained are due to the greater discrimination against interfering signals achieved in the design of systems and the ease with which polar diagrams can be controlled.

B.2 Perhaps the most significant microwave propagation characteristic is the effect of 'shadowing' and diffraction on the signal-to-noise ratio of systems. One must consider the following; (a) the effect of losses due to buildings, trees etc. in relation to the required coverage and range of operation, (b) the effect of aircraft landing, taxiing or parking on the signals received by other aircraft approaching or landing and, (c) the effect of runway contours on the guidance 'integrity' in the last stages of landing and first phase of roll out. Ideally a single line-of-sight path between transmitter and receiver is required under all conditions - but in any practical situation this is unlikely to be obtained or maintained.

B.3 The theory of shadowing is based on Sommerfelds[8] work and Rice[9] has developed two methods of computing the losses behind 'knife edge' or 'parabolic shaped' ridges. The theory makes simplifying assumptions concerning the physical properties of the obstacle causing diffraction but even then the computation required for each case is tedious.

B.4 The general equation relating to the configuration shown in Fig.7 is given by

$$L_D = \frac{1}{2} - \frac{1}{1 - j}[C(a) - jS(a)] \tag{B-1}$$

where L_D is the loss in the presence and the ridge (see for instance Starr[18]) $C(a)$, $S(a)$ are Fresnel integrals and

$$a = h\left\{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)\right\}^{\frac{1}{2}} . \qquad \text{(B-2)}$$

The parameter (a) is related to the path difference (δ) between the unobstructed line-of-sight path and the diffracted path in the presence of the ridge. The relation is

$$a^2 = \frac{4\delta}{\lambda} .$$

It can be seen that when the transmitter and receiver are in line with the diffracting edge (e.g. the depression angle (γ) Fig.7 is zero) then δ and a are zero and the loss 6 dB.

B.5 In order to obtain loss figures related to C band operation in practical airfield situations a programme of measurements has started at RAE. Some preliminary results are available and can be compared with the theory.

B.6 <u>Effect of trees</u>

Fig.8 illustrates the experiment. A C band transmitter was arranged at the point shown (near the end of a runway) and its directional aerial adjusted to be either 5 feet or 18 feet above the ground and pointing in turn in the NSEW directions. An aircraft with a C band aerial and receiver was then flown towards the transmitter from each of the directions and at a series of heights (500, 1000 and 2000 feet). Recordings of signal strength as a function of range from the transmitter were taken for each test. The view to the east was unobstructed while the North (1) and (2), south and west directions were obstructed by trees. The trees to the west and south were bare of leaves and not dense; to the north they were evergreen (coniferous) and from North (2) the propagation path was shielded by a large building (see Fig.15). As well as siting the aerial at 5 and 18 feet height above ground the trials were repeated for horizontal and vertical polarisation. A summary of the measurements made is given in the following table.

Flight direction from	Tx aerial height (ft)	Crest angle	Polarisation	Aircraft height (ft)
North (1)	5	1.0^{o}	VP	500
North (2)	5	1.6^{o}	VP	500
West	5	10.0^{o}	HP VP	400 and 1000 500
West	18	6.2^{o}	HP VP	500, 1000 and 2000 500, 1000 and 2000
South	5	10.6^{o}	HP VP	500 and 1000 500 and 1000
South	18	8.0^{o}	HP	500, 1000 and 2000

The visibility was not good enough to complete all the programme at the 2000 feet and 1000 feet levels but each of the other tests were repeated at least twice. In addition to the microwave transmission a recording was made of a 100 Mc/s transmission from a dipole one wavelength above ground and directed along each approach direction.

B.7 Results

Typical results have been plotted in Figs.9-14 showing the loss with respect to the unobstructed path to the east as a function of aircraft depression angle below the crest. The following conclusions have been reached.

(1) The effect of trees on the VHF transmission 100 Mc/s was very small (about 3 dB over a 6^{o} depression angle).

(2) The attenuation of the C band signals began at a crest angle (α) corresponding to the line from the transmitter to the tops of the trees. This is shown by the similarity of the results obtained at different aircraft heights (2000, 1000 and 500) and presented as a function of aircraft elevation with respect to the transmitter. The small variations in the onset of attenuation is most likely due to differences in the azimuth position of the aircraft on successive runs and the irregular height and density of the trees (see Fig.15).

(3) The measurements did not reveal any significant difference in the losses from vertical and horizontal polarisation.

(4) The measured attenuations varied between 6 dB and 15 dB per degree of depression angle. However the receiver sensitivity was insufficient to allow

attenuations more than 30 dB below the unobstructed value to be measured and the curves obtained suggest that the attenuation per degree increases with increasing depression angle. It will also be noticed that (Fig.15) a definite 'hard' crest exists at about ½ the tree top crest angle and there is evidence in the measurements that the attenuation increases markedly at depression angles below this secondary crest.

(5) Raising the transmitter aerial improves the propagation at low angles in direct relation to the geometrically lower crest angle.

(6) Some records, both from horizontal and vertical transmissions showed deep fading within the overall attenuation envelope. It is thought that this may have been due to differing flying conditions and the irregular density of the trees.

(7) The trial from the north indicated deep fading at shallow depression angles below a shadowing building. More tests are needed to establish whether this is a consistent effect. It should be noted that the normal range/signal strength curve is a function of both ground and aircraft aerial vertical polar diagrams.

B.8 Shadowing due to taxiing aircraft

There will be many instances where an aircraft will taxi or roll out within the near coverage of the guidance system. For instance on a STOL runway of 2000 feet length aircraft will tend to use most of the runway length and may turn off within 500 or 1000 feet of a localiser sited at the stop end. Some tests are being carried out to investigate the effects of shadowing due to aircraft. It is intended to determine the propagation losses, and the effect on time, phase and angle measurements. A first series of tests has measured the losses in one configuration. The experimental arrangement is shown in Fig.16. The transmitter with vertically polarised aerial was sited 4 feet above the runway and 500 feet beyond the intersection of two runways. A receiving aerial was sited 2000 feet away from the runway intersection and by using a telescopic mast its height could be varied up to 70 foot above the runway surface. It will be seen from Fig.16 that the runway contour also has an appreciable slope which has been accommodated in the analysis of results.

The aircraft used to produce the shadow was a Hawker Siddeley 748. It is a medium to small aircraft with STOL characteristics. The body height is 15 feet and the tail height 28 feet above the ground. The underside of the body clears the ground by 5 feet. In the tests the receiving aerial was first moved in steps

up to 70 feet and the received signal level recorded. This measured the undisturbed signal distribution with height. The receiving aerial was then set at a series of heights and the 748 was towed slowly across the runway intersection. A recording of signal strength was made in relation to the aircraft nose position with respect to the line-of-sight.

B.9 Results

The results are summarised in Figs.17-20 and the following comments can be made.

(1) The losses exceeded the knife edge theory (Fig.19) on average by about 6 dB per degree of depression angle. The loss at the crest angle approximates to the 6 dB predicted by theory and an enhancement of the signal above the crest angle is also observed.

(2) The loss does not go on increasing as the receiving aerial is lowered. It shows a tendency to stabilise or even decrease and this appears to be due to propagation and diffraction of energy under the body of the aircraft.

(3) The tail fin produced the biggest loss and this is a straight extrapolation of the results obtained from the body, i.e. the receiver could now be moved through a greater depression angle before the propagation path under the aircraft became effective.

(4) The effect of the 'under body' path can be seen from Fig.20 which shows the effect of rolling the aircraft out along the runway towards the transmitter and then turning it and returning to the receiver. The signal attenuation increases until a maximum loss is recorded and then the loss is lessened by the new path.

(5) The results emphasise that the simple theory can only be used to indicate trends. A more exact analysis would need to compute and combine the losses resulting from all possible ray paths, and take greater account of the aircraft body shape.

(6) The analysis of results is not complete and a number of interesting features need further examination. The occasional large loss just after passage of the nose (Fig.17) is an example.

(7) The work needs to be extended particularly to the problems of 'humped' runways and also to determine the effect of the losses on the accuracy of guidance.

B.10 Summary

The empirical results so far show that shadowing losses are much greater than those experienced at VHF, and in many instances more severe than predicted by diffraction theory. It is necessary to think of the problem in conjunction with the difficulty of providing an 'all round looking' aerial on aircraft and their combined effect on signal integrity.

In typical airfield environments thought must be given to the siting and height of the transmitting aerials in order to avoid permanent or intermittent loss of signal in parts of the coverage. It will be important to determine the effect that shadowing may have on the integrity of guidance throughout the landing phase.

Appendix C

GUIDANCE FIELDS AT LOW HEIG

C.1 The mechanism of direct and reflected wave interference is well known. It is particularly important in relation to guidance systems since many of the operational requirements call for continuous high quality guidance when the aircraft is descending at low heights or rolling out along the runway.

The possible geometries are shown in Fig.21. In (a) the path difference between the reflected and direct wave is given by $2h_2 \sin\gamma$ and the phase difference between the waves $\frac{4\pi h_2 \sin\gamma}{\lambda}$. Similarily in case (b) the phase lag on the reflected wave is $\frac{4\pi h_1 h_2}{\lambda d}$.

In (a) the total received wave (E_R) can be represented by

$$E_R = \cos wt + r\cos\left(wt - \psi - \frac{4\pi h_2 \gamma}{\lambda}\right)$$

where the ground reflection coefficient = $r \exp - j\gamma$.

From this the amplitude

$$|E_R| = \left\{1 + r^2 + 2r\cos\left(\psi + \frac{4\pi h_2 \gamma}{\lambda}\right)\right\}^{\frac{1}{2}} . \qquad \text{(C-1)}$$

C.2 In the guidance situation the height h_1 of the transmitter will be small (in feet) although inevitably many wavelengths at C band. The critical aircraft receiving aerial heights will be from about 300 feet, following a glide slope to about 10 feet above the runway when the aerial will stay at this height during the roll out. The important range of distance (d) from the transmitter to the aircraft aerial will vary between about 1000-5000 feet for a STOL aircraft landing along a 6° glide path into a 2000 foot runway, and between 2000-18000 feet for a CTOL aircraft landing on a 12000 foot runway from a 3° glide path.

C.3 In both these cases the transmissions reach the aircraft near grazing incidence, i.e. γ is small. For this condition the reflection coefficient $\to 1$ and the phase angle $\psi = \pi$ for both horizontally and vertically polarised waves.

Equation (C-1) therefore becomes

$$|E_R| = \left\{2 - 2\cos\frac{(4\pi h_2\gamma)}{\lambda}\right\}^{\frac{1}{2}} ,$$

i.e.

$$|E_R| = 2\sin\frac{(2\pi h_2\gamma)}{\lambda} \quad \text{.......... case (a)} \qquad \text{(C-2)}$$

or

$$2\sin\frac{(2\pi h_1 h_2)}{\lambda d} \quad \text{.......... case (b)} \quad . \qquad \text{(C-3)}$$

It can be seen that the signal will contain 'holes' which will occur when $\gamma = \frac{n\lambda}{2h_2}$ (n = 0 or a positive integer), lasting for periods determined by the aircraft speed. As γ increases it may be possible to reduce the depth of the nulls by designing the transmitting aerials to limit the power radiated into the ground. This will require a polar diagram loss of ℓ dBs within an angle β. (β is the angle (Fig.21) between the direct and the incident ground ray. $\beta \approx \frac{2h}{d} \approx 2\gamma$.)

The value to assign to ℓ will depend on

(a) the threshold allocated to a flag warning which is usually related to signal strength,

(b) the tolerable effect on guidance of a signal drop out, bearing in mind that even in a balanced guidance system the aircraft may not be aligned with the course zero.

C.4 Typically one might require the fading depth to be limited to 25% which would call for a polar diagram loss of 12 dB over the angle β. In many cases, however, β will be less than 1^o and this in conjunction with the requirement for broad coverage in elevation will limit the possibility of polar diagram shaping.

C.5 It is instructive to look at the following cases.

(a) A STOL aircraft descending a 6^o glide path to the runway with touch-down 2000 feet from the localiser or DME position.

(b) A CTOL aircraft descending a 3^o glide path to the runway with touch-down 12000 feet from the localiser or DME position.

(c) As for (b) but with an intermediate 7000 feet distance between localiser, DME and touchdown.

Each of these cases has been evaluated for two transmitting aerial heights, 5 and 20 feet, and the results are shown in Figs.22, 23 and 24.

C.6 Comments

The general patterns can be envisaged by inspection and the aim in any design must be to minimise the depths of the nulls. The most difficult problems will occur on long CTOL runways in respect of localiser and DME signals in the region of touchdown.

C.7 Choice of aerial height

At microwaves it is not feasible to locate the aerial phase centre within one or two wavelengths above ground (as for instance at VHF). The aerial height is first of all constrained by the aperture dimensions needed for any vertical directivity, but also by the need to obtain some clearance above grass, rough ground, uneven runways etc. and also for snow clearance. The figure of 5 feet is taken to be a reasonable lower height for a C band localiser. In addition a low aerial height will increase problems due to diffraction losses from shadowing buildings, trees or taxiing aircraft so that in many instances it will be desirable to site the aerial as high as possible. It can be seen that the diffraction and fading effects produce a conflict with respect to optimum siting.

C.8 Aerial vertical directivity

Again there is a conflict produced by the ORs. The requirement is for (see Appendix A) up to 20° (30° desired) and down to 5 feet above the runway surface into the undershoot* for a distance of 0.5 n miles. The first requirement calls for a relatively small aerial aperture, the second for a wide aperture. As part of the RAE programme an aerial is being designed to produce in effect a composite pattern. The design aim is shown in the polar diagram of Fig.25. This would apply to a distance or azimuth measuring system in which the aerial polar pattern plays a subsidiary role in forming the guidance fields. In the case of an aerial directive system such as a scanning beam or 'Doppler' ILS the same sort of vertical pattern could be mated to the required azimuth directivity. Alternatively there would be merit in considering a 'raster' scan to enable both azimuth and vertical directivity to be used.

C.9 Angle/DME computed flare guidance

In order to use an elevation guidance system to compute flare it must be sited upwind of the required touchdown point (about 1000 feet beyond touchdown)

*This requirement for guidance down to 5 feet in the undershoot is related in one OR to vertical guidance. However in practice it would be pointless to provide vertical guidance in a sector where azimuth and DME measurement had failed.

to avoid near field effects. If this is mated to the requirement for coverage into the undershoot then this will call for guidance down to 0.05° from the transmitting aerial. If we allow a 10 dB differential between the direct and ground incident ray then by reference to say a scanning vertical beam pattern with 18 dB first sidelobes we find that the main beam must be 0.64° between the ±10 dB points. This requires an aperture of 30 feet at 5000 Mc/s or 10 feet at 15000 Mc/s. The C band aerial would be at a disadvantage since its phase centre would be at least 15 feet above ground (the requirement is then actually worsened) while the 15000 Mc/s aerial could just be sited with its centre at 5 foot height if no ground clearance is allowed.

For the DME element the two questions to be resolved are (a) its position relative to touchdown and (b) its vertical polar diagram. Unless the DME is to be a special to type system just for flare guidance then it is necessary to assume that the other DME requirements will restrict the options with respect to (a) and (b). This overall DME requirement is discussed in Appendix D.

Appendix D

SUBSYSTEM GEOMETRY RELATED TO POSITION MEASUREMENT

To measure an aircraft's position in space relative to the runway the guidance systems must provide an azimuth measurement (θ or $\cos\theta$), an elevation measurement (ϕ or $\cos\phi$) and a distance measurement R. Since the ground subsystems may be located in a number of places relative to the runway, and because runway lengths vary from airfield to airfield it will also be necessary to know additional information concerning the geometrical constants. The most likely positions are shown in Fig.26. The combination $D_1\theta_1$ represents the conventional upwind position for the azimuth and distance measuring element. $D_2\phi_2\theta_2$ represent distance, elevation and azimuth measurement from a site upwind from the touchdown point and suitable for an angle/distance computed flare. $D_3\phi_3\theta_3$ and are the respective subsystems at normal glide path origin, (i.e. offset close to touchdown). $D_4\theta_4$ are distance and azimuth subsystems positioned in the undershoot. The distances d_1 to d_7 determine the subsystem positions with respect to the runway threshold. It is also assumed that a runway identification (i) is needed together with a runway bearing (β) which may be necessary to orientate situation displays with respect to other aircraft instruments. Two types of guidance system are considered - one providing constant guidance over planar surfaces and the other over conical surfaces.

As a first step we can tabulate the aircraft derived information necessary to compute the manoeuvres required to satisfy the required classes of operation, (i.e. curved approach paths; curved descent paths; curved approach and descent paths; flare out; decision height measurement; curved overshoot paths; distance to threshold; distance to go during roll out). It is assumed that in the case of STOL and CTOL aircraft the objective will always be to align the aircraft with the runway centre line and the final glide path angle at least 2000 feet before reaching runway threshold. From Fig.26 the following Table D1 has been compiled, to show the main combinations of subsystems that could satisfy each requirement. The distance measuring (D_1 to D_4) element has been chosen as the reference point for the other subsystems.

D.1 Curved approach paths

The aircraft requires to measure its lateral error with respect to some prescribed track. This track relative to the runway approach must be made known to the pilot through the aircraft instrumentation, together with the error

and error rate signals derived from the measurements of position. The runway identification (I) and bearing (ß) are needed to relate the aircraft heading to the actual runway direction. In addition from each position the co-ordinates of the distance and azimuth measuring subsystems with respect to thr shold must be communicated to or stored in the aircraft. In the case of positions (D_2, D_3) the offset distances d_6, d_7, must be provided if alignment with the runway centre line is required.

D.2 Non-linear overshoot paths

The aircraft may need to be vectored away from an adjacent parallel runway in an overshoot. In addition go-around guidance might be provided. Clearly this calls for forward and rearward looking coverage and this could be provided from one position or by combining transmissions from two positions. In the table therefore θ_1, could represent an upwind localiser with a back beam while θ_4 could apply to a reciprocal or separate localiser mating into an up... ...proach system. The additional examples are other combinations which mi... be ... ed.

It should be noted that in an overshoot the aircraft will pa... distance and azimuth systems at varying heights. This may give rise ... in the coverage due to polarisation and polar diagram effects and in the case of the distance subsystem, there will be a variable minimum to the range measurement. In the D_1, D_4 in-line positions these minima are height measurements. The position D_4 is probably the least desirable position operationally, since it will always be essential to avoid loss or degradation of signal in the region of runway threshold. In addition the use of a reciprocal localiser at the D_4 position for overshoot may be ruled out in many instances since its transmissions may effectively 'jam' the wanted approach systems signals during landing.

D.3 Non-linear descent paths

The descent paths are computed from elevation and distance measurements in addition to the appropriate geometrical constants. If the elevation subsystems are 'conical' then the correct height measurements are provided at all azimuth angles. For 'planar' subsystems (see Appendix E) height must be computed with respect to the azimuth angle measurement, and the most suitable combinations would be $D_1\theta_1\phi_3$ or $D_3\theta_3\phi_3$ while for a 'conical' system either $D_1\phi_3$ or $D_3\phi_3$ would provide the required service.

D.4 Non-linear approach and descent paths

This is the complete system providing the greater flexibility but involving the most complexity. The combinations of greatest interest are the $D_1\theta_1\phi_3$ and $D_3\theta_3\phi_3$. Again these are appropriate to either 'planar' or 'conical' systems and it will be noted that the conical combinations could comprise of an orthogonal azimuth system and this will ther be capable of providing complete hemispherical measurement with some simplification of the computation (Appendix E). It has been suggested that the use of orthogonal conical subsystems can be used to effect a conical to planar conversion. Although this is true, it would appear to be of little consequence since the proper use of such systems allows any profile to be computed.

D.5 Flare guidance

This has been raised as a requirement to provide an alternative to radio altimeter control for flare guidance. Height and its rate of change must be computed from angle of elevation and distance. The elevation subsystem must be sited upwind of the touchdown point (by probably at least 1000 feet) to avo near field distortions and ease coverage problems so that two main choices fo the distance element exist at D_1 and D_2. On very long runways the propagation problems may make the $D_2\phi_2$ combination a better choice than $D_1\phi_2$ particularly for a conical system which would need no azimuth correction. The $D_3\phi_2$ alternative is included since during the flare the distance accuracy required is not stringent and could if necessary, be supplemented by integrating velocity. It should be noted that the origin height (h_ϕ) must be known and on some runways the knowledge of the surface contours between ϕ_2 and threshold may be desirable.

D.6 Decision height measurement and distance to threshold

These are straightforward applications of the distance measuring subsystems with some preference for the $D_3\phi_3$ position (see D.7).

D.7 Distance to go during roll out

Measurements can be made from the D_1 position when the distances d_1, d_5, are also known. Measurements from the D_3 position would be acceptable assuming that the distance minimum opposite glide path origin is not objectionable. In practice a distance indication with a minimum reading close to touchdown could have advantages for approach, roll out and overshoot, and this would suggest the use of glide path origin rather than runway threshold as the

reference point. Fig.27 shows the D_3 distance function compared with that from the D_1 position for a constant aircraft speed of 200 feet/second during final landing and first stages of roll out. The D_3 function would appear to simplify the display of distance information.

D.8 Summary

There are three main configurations which can satisfy all the requirements; namely $D_1\theta_1\phi_3\phi_2$ related to planar or conical systems and $D_3\theta_3\phi_3\phi_2$ or $D_3\theta_1\theta_3\phi_3\phi_2$ more suited to conical. The question of flare guidance - and the integrity problems that it involves - may make distance measurement from the D_1 position the least reliable for long runway operation. It should be noted that the $D_3\theta_3\phi_3$ combination where θ_3 consists of an orthogonal azimuth subsystem, satisfies all the requirements except perhaps for Category II and III CTOL or STOL landing operations. It probably would need to be supplemented by a θ_1 azimuth subsystem for final approach and touchdown. This arises because the alignment accuracy between the guidance signal and the runway centre line should be maintained within about ±1 foot. In the case of the $D_3\theta_3$ position the alignment is purely a function of the distance measuring accuracy and it is unlikely that distance measurement of such accuracy would be obtained or justified in a practical system. In addition the aircraft will pass through an angle of $\pm 45^{\circ}$ in about 5 seconds, so that data rate and polar diagrams may present problems. However the $D_3\theta_3\phi_3$ combination has advantages for VTOL operations and it has been suggested that such systems could provide 'offset' tracks to more than one landing area. In all applications the distance subsystem could be a critical component to site and operate and it should be noted that D_3 is the only position relative to the runway which could be standardised at the majority of airfields.

In the context of the operations listed in Table D1 aircraft will require error and error rate information with respect to the xyz axes, and therefore there should be a strong preference for a direct cartesian measurement. The situation has been confused because although the majority of guidance techniques generate 'conical' guidance surfaces there is a class of scanning beams which can be simply designed to be planar. This has led to statements, supported by little worthwhile argument, that planar guidance is essential and conical systems unacceptable[8]. The choice of co-ordinate system is discussed in Appendix E.

Table D1

	Distance measuring system position			
	D_1	D_2	D_3	D_4
Curved approach	D_1 θ_1 l β — d_1 d_5	D_2 θ_2 l β — d_1 d_2 D_2 θ_1 l β — d_1 d_2 d_5 d_7	D_3 θ_3 l β — d_3 d_6 D_3 θ_1 l β — d_1 d_3 d_5 d_6	D_4 θ_4 l β — d_4 D_4 θ_1 l β — d_1 d_4 d_5
Curved overshoot	D_1 θ_1 l β — d_1 d_5 D_1 θ_4 l β — d_1 d_4 d_5	D_2 θ_2 l β — d_2 d_7 D_2 θ_1 l β — d_1 d_2 d_5 d_7 D_2 θ_4 l β — d_2 d_4 d_7	D_3 θ_3 l β — d_2 d_6 D_3 θ_1 l β — d_1 d_3 d_5 d_6 D_3 θ_4 l β — d_3 d_4 d_6	D_4 θ_4 l β — d_4 D_4 θ_1 l β — d_1 d_4 d_5
Curved descent	D_1 ϕ_3 — d_1 d_3 d_5 d_6	D_2 ϕ_3 — d_2 d_3 d_6 d_7	D_3 ϕ_3 — d_3 [illegible] (θ_1 or θ_3 if planar)	D_4 ϕ_3 — d_3 d_4 d_6
Curved approach and descent	D_1 θ_1 ϕ_3 l β — d_1 d_3 d_5 d_6	D_2 θ_1 ϕ_3 l β — d_1 d_2 d_5 d_3 d_6, d_7	D_3 $\theta_3 \theta_1$ ϕ_3 l β — d_1 d_3 d_5 d_6 D_3 θ_1 ϕ_3 l β — d_1 d_3 d_5 d_6	D_4 θ_4 ϕ_3 l β — d_1 d_3 d_4 d_6 D_4 θ_1 ϕ_3 l β — d_1 d_3 d_4 d_5 d_6
Flare	D_1 ϕ_2 h — d_1 d_2 d_5 d_7	D_2 ϕ_2 h — d_2 d_7 (θ_2 or θ_1, d_1, d_5, if planar)	D_3 ϕ_2 h — d_2 d_3 d_6 d_7 θ_1, d_1, d_5 or θ_3	
Decision height measurement	D_1 ϕ_3 — d_1 d_3 d_5	D_2 ϕ_3 — d_2 d_3	D_3 ϕ_3	
Distance to threshold	D_1 ϕ_3 — d_1 d_3 d_5	D_2 ϕ_3 — d_2 d_3	D_3 ϕ_3 d_3	
Distance to go during roll out	D_1 — d_1 d_5	D_2 — d_1 d_2 d_7	D_3 — d_1 d_3 d_6	D_4 — d_1 d_4

Appendix E

THE CO-ORDINATE MEASURING SYSTEM

E.1 An important factor to be decided is the co-ordinate system to be adopted for position measurements. The problem has been posed as a choice between 'planar' or 'conical' guidance (i.e. the lines of constant guidance lie either on plane or conical surfaces). It is relevant to note that planar guidance fields are produced by mechanically nodding or rotating a fan beam coded with pointing angle, whilst most other techniques generate time, phase, frequency or amplitude varying fields with conical contours.

The planar systems in conjunction with slant range measurement give co-ordinates $(R\theta)$ and the conical provide direction cosines which with slant range $(R \cos \theta)$ give directly the cartesian co-ordinates of a point. Clearly either can be adapted to provide three dimensional position fixing. However the practical operation of microwave guidance systems will be dependent on a number of factors such as subsystem combination and siting (Appendix D) as well as the range of operational requirements. It is necessary therefore to examine the alternatives and implications in some detail.

E.2 Planar and conical geometry

The differences between the planar and conical geometries are illustrated in Fig.29. In each case the locus of the spatial positions P_1P_2 etc., lie on circles. However, in the planar geometries these circles are centred on the origins, O, and have a radius R equal to the slant range from the origin whilst in the conical case the circles are the bases of cones which are symmetrical about the measuring systems axis, have their vertex at the origins, and have a base radius determined by both the slant range (R) and angles θ or ϕ. The difference between the planar angles θ_p, ϕ_p and the conical angles θ_c, ϕ_c should be noted.

E.3 The aircraft requirements

In the comparison that follows, it is assumed that the aircraft receives a distance measurement R and the planar pointing angles θ_p, ϕ_p or the conical direction cosines $\cos \theta_c$, $\cos \phi_c$. From these it will in general need to compute its linear displacement from the xyz axes (z = height, y = lateral displacement, x = longitudinal displacement) since these displacements and their derivitives are the essential inputs to displays and automatic flight control systems. In the simplest applications (normal ILS approaches for instance) it

is of course only necessary to know the angles θ, ϕ and their origins - but we are concerned here with the computation of errors in relation to non-linear spatial tracks and both the position measurement and the storage of track co-ordinates is most easily handled in linear cartesian form.

E.4 Planar elevation

The subsystems will provide in the aircraft a measurement of slant range R and elevation angle ϕ_p. For normal ILS approaches the aircraft can couple directly to the preferred glide path angle and with a planar system sited at the side of the runway this angle remains correct with respect to the y axis for approaches parallel to the x axis. However, during the last stages of landing the flare manoeuvre is most easily performed manually or automatically controlled with respect to height above the runway so that the plane surface ceases to be of importance. The automatic programme must be sufficiently flexible to permit recomputation of the flare profile in the event of any disturbance in the flight path during landing. In the case of the planar $R \sin \phi_p$ related to the origin O, computed height must be corrected with respect to azimuth angle. To achieve this the distance element maybe separated from the elevation measurement and sited in line with the direction of approach. In this case the distance between the distance and elevation subsystems must be transmitted to the aircraft, together with the elevation origin height above the runway. In the context of position $D_1\phi_2$ of Fig.26,

$$h \approx \{R - (d_5 + d_1 - d_2)\} \sin \phi_p - h_\phi \tag{E-1}$$

where R is the slant range measurement from D_1, and assuming that the aircraft is correctly aligned with the runway centre line and that $R \gg h$.

A further application where the height error with azimuth displacement is important, is in non-linear descent during approach. In this case the correct height must be computed with respect to the measurement of azimuth angle. In the $D_1\theta_1\phi_3$ combinations the general equation for height becomes

$$z \approx h = \{x - (d_1 + d_5 - d_3)\} \tan \phi_p$$

where x is given in equation (E-15).

It should be noted however, that in practice the elevation data will fail at large azimuth angles from the elevation site due to limits on elevation

system coverage and polarisation difficulties and that the equation tends in these regions to be undeterminate since $\phi_p \rightarrow 90^o$.

E.5 Conical elevation

The conical elevation system (Fig.29) together with a cosited slant range measurement provides the cartesian co-ordinates z (i.e. height, h) directly from the measurement $R \cos \phi_c$ at all azimuth angles. If the distance measuring subsystem is not sited at the elevation origin then the effective slant range R must be computed from the siting constants. For instance in the case of the flare guidance combinations $D_1\phi_2$, assuming $R \gg h$ and the aircraft is aligned with the runway centre line.

$$h = \{[R - (d_1 + d_5 - d_2)]^2 + d_7^2\}^{\frac{1}{2}} \cot \phi_c - h_\phi \quad . \tag{E-3}$$

In the case of the split site combination $D_1\theta_1\phi_3$ for computing non-linear descent paths

$$z = h = \left\{R^2(1 - \cos \theta_c) - x^2\right\}^{\frac{1}{2}} \tag{E-4}$$

where x is given in equation (E-18).

It should be noted that in these cases the variables, $\cos \phi_c$, $\cos \theta_c$, and R are measured directly so that the equations can be treated algebraicly.

E.6 Planar azimuth

The subsystems will provide a measurement of slant range, R, and angle measured with respect to the runway centre line. If we consider the $D_1\theta_1$ position then the lateral displacement from the plane perpendicular to the runway centre line (xz plane Fig.29) is given by

$$y = (R^2 - h^2)^{\frac{1}{2}} \sin \theta_p \quad . \tag{E-5}$$

This of course reduces to $R \sin \theta_p$ if $R \gg h$. In the case of an azimuth and distance subsystem used to compute plan position without knowing either height or slant angle of the range measurement there is a height dependent error in the direction of the origin at all azimuth angles equal to

$$\{R - (R^2 - h^2)^{\frac{1}{2}}\} \quad . \tag{E-6}$$

The general solution for y in the case of the full $D_1\theta_1\phi_3$ combinations is given by

$$y = x \tan \theta_2$$

where x is given in equation (E-15).

E.7 Conical azimuth

If we consider the $D_1\theta_1$ position with the subsystems providing R and $\cos\theta_c$ then the displacement y from the plane perpendicular to the runway centre line (the xz plane) is given by

$$y = R\cos\theta_c \tag{E-7}$$

at all azimuth angles. In an azimuth - distance subsystem used to compute plan position without knowing either height or slant range of the range measurement, the true plan position moves parallel to the x axis from its position in the xy plane at zero height (P_1 Fig.29) towards the y axis. The height dependent error measured from the indicated position P_2 is

$$E = \{R^2 - y^2\}^{\frac{1}{2}} - \{R^2 - y^2 - h^2\}^{\frac{1}{2}} \ . \tag{E-8}$$

In both the planar and conical case a height measurement from the aircraft's altimeter would remove the significance of the errors.

E.8 Orthogonal conical systems

Since conical systems supply angular information in terms of $\cos\theta_c$ or $\cos\phi_c$ the accuracy and usefulness of a single co-ordinate system decreases as θ_c or ϕ_c tend towards zero. By combining two systems in the form of a cross, a sin-cosine or orthogonal system results which now measures

$$y = R\cos\theta_{cy} \tag{E-9}$$

and

$$x = R\cos\theta_{cx} \ . \tag{E-10}$$

In addition a measurement of z (height h) is also obtained from the relation

$$z^2 = h^2 = R^2 - y^2 - x^2 \quad . \tag{E-11}$$

The complete spatial solution is given by adding the third subsystem orthogonal to the xy plane to give

$$z = R \cos \phi_c \quad . \tag{E-12}$$

It will be noted that this arrangement now has redundancy of measurement which provides a reasonably uniform accuracy throughout the hemisphere since at all times two of the three systems are near optimum.

E.9 Split site conical systems

The advantages of employing a colocated three axis conical system, are evident. However, there is the problem of azimuth alignment with the runway centre line (Appendix D) and the need to provide good coverage to aircraft, many of which may have forward looking aerials, during the landing and roll out along the runway. There are two ways in which these problems may be overcome.

The first configuration would separate the azimuth and elevation subsystems and site them in the conventional ILS configuration, (the $D_1\theta_1\phi_3$ arrangement). In this case the orthogonal y axis component could be located at either the D_1 or the D_3 site.

The second method of correctly aligning the azimuth system is to split the axis of the y subsystem so that it can straddle the runway with the xz plane of electrical symmetry aligned with the runway centre line. This can be accomplished, either colocated at the D_3 position or at any convenient position along the runway length. In these cases it may be necessary to locate the distance measuring element at the D_3 position.

E.10 The addition of an accurate distance measurement to the basic azimuth and elevation functions, enables the aircraft's position to be determined and clearly either planar or conical guidance fields can be adapted to this use. Two ways of computing the xyz co-ordinates are; (a) to use the range R and planar angles θ_p or ϕ_p together with the position co-ordinates of the ground subsystems in a manner similar to that used with VOR/DME. In this case however, the general approximation will not always be valid since often the slant range/height ratio will be small enough to contribute significant errors. The second method, (b) is to use the conical direction cosines together with

slant range and subsystem position co-ordinates to compute the xyz displacements from the axes. In the case of an orthogonal azimuth system aligned with the xy axes the relevant terms are given by (E-9) and (E-10)

$$y = R \cos \theta_{cy}$$

$$x = R \cos \theta_{cx} \ .$$

In the majority of cases the ground installations will comprise azimuth, elevation and distance measuring subsystems in a split site configuration corresponding to the $D_1\theta_1\phi_3$ combinations. It is now necessary to use the following general equations to solve for x, y and z. If we let the siting constants $(d_1 + d_5 - d_3) = D$ then in the planar $D_1\theta_{p1}\phi_{p3}$ case

$$y = x \tan \theta_p \qquad \text{(E-13)}$$

$$z = (x - D) \tan \phi_p \qquad \text{(E-14)}$$

$$x = \frac{D \tan^2 \phi_p \pm \{R^2 (\sec^2 \theta_p + \tan^2 \phi_p) - D^2 \sec^2 \theta_p \tan^2 \phi_p\}^{\frac{1}{2}}}{\sec^2 \theta_p + \tan^2 \phi_p} \ . \qquad \text{(E-15)}$$

In the conical $D_1\theta_{c1}\phi_{c3}$ case

$$y = R \cos \theta_c \qquad \text{(E-16)}$$

$$z = \{R^2(1 - \cos^2 \theta_c) - x^2\}^{\frac{1}{2}} \qquad \text{(E-17)}$$

$$x = D \cos^2 \phi_c \pm \{D^2 \cos^2 \phi_c (\cos^2 \phi_c - 1) + 2Rd_6 \cos \theta_c \cos^2 \phi_c + d_6^2 \cos^2 \phi_c + R^2(1 - \cos^2 \theta_c) - R^2 \cos^2 \phi_c\}^{\frac{1}{2}} \ . \qquad \text{(E-18)}$$

In addition if the conical azimuth system consists of the orthogonal θ_{cx} and θ_{cy} then the solutions are simplified to

$$y = R \cos \theta_{cy} \qquad \text{(E-19)}$$

$$x = R \cos \theta_{cx} \qquad \text{(E-20)}$$

$$z = \{(x - D)^2 + (y + d_6)^2\} \cot \phi_c \ . \qquad \text{(E-21)}$$

The distance measurement maybe obtained from an interrogator-transponder system - similar to the L band DME or Tacan systems. Alternatively it is possible that a one way ranging technique based on highly stable frequency generation and time measurement will be developed and adopted. The latter method has many attractions one of them being that the measurement could be integrated into each of the azimuth and elevation subsystems so providing an independent slant range measurement to each angular origin, and a considerable simplication in the airborne computation and operational use of the systems.

Appendix F

ACCURACY AND FLIGHT SYSTEM COMPATIBILITY

F.1 Basic requirements

The operational requirements do not state the accuracies required specifically but rather by implication and reference to the ICAO VHF ILS Specifications. With a microwave ILS it will be necessary to establish criteria appropriate to the different classes of system and the following notes illustrate the issues involved.

With VHF ILS the accuracies are regulated in terms of beam noise (the beam bend specifications) and static alignment errors. The parameters that have evolved as a result of experience with many aircraft and flight control systems are given in Appendix A. The most important point to be noted is that the sensitivity variations implied in angular systems have been regulated by making the elevation and azimuth guidance functions standard at the runway threshold (i.e. the control signal in $\mu A/^{o}$ should be common to all runways at the threshold). This problem will need to be faced with the microwave system but is complicated by the fact that θ and ϕ must be true angles at all runways. (This is one of the consequences of moving away from guidance to position measurement.) From the point of view of flight control systems the requirement for uniformity and not to exceed stability margins remains, so that alternative methods to that of threshold sensitivity standardisation must be sought.

When a distance measurement is added to the azimuth and elevation measurements then the solution is simply one of linearising the information as a function of distance to go - and this leads directly to the opportunity for computing xyz. In this case the displacement sensitivities remain constant but the signal/noise ratio of the guidance signals will vary with range from origin.

For guidance systems which do not include the distance measuring subsystem the problem is not so simple. One method would be to code the azimuth transmission with data giving the runway length. This could then be used by the receiver to program the required sensitivity change. An extreme operational case which should be considered is that of STOL aircraft which maybe required to operate into either STOL or CTOL runways with a possible runway length variation of 6:1. It is interesting to note that in ground computer controlled systems such as the interferometric (MADGE) the problem is solved since each runway's parameters can be set into the ground station and a single sensitivity law is adopted as common to all aircraft.

F.1.1 Localiser accuracy

For a VHF ILS localiser the Category III long runway requirement can be interpreted as about 10 foot peak (2σ) for beam noise and 10 foot (never to be exceeded) static error measured at the runway threshold. If we deal in one sigma values and note that both signal/noise and alignment accuracy can be improved marginally in a microwave ILS then these runway threshold values could be set to 3 feet (1σ). This means that for a 12000 foot CTOL runway we require the long term stability in alignment and the beam noise of the azimuth system to be within 0.014°. It may be argued that in the case of a STOL runway (2000 feet), these angular accuracies could be relaxed to 0.1° since this will maintain the displacement tolerances at runway threshold sufficiently tight. However it must be remembered that rate of change of angular sensitivity will be much greater in STOL operations and it may be the position measuring accuracy at maximum range that is the important factor. This is considered later.

F.1.2 Glide path accuracy

The VHF glide path accuracy is given in Appendix A and is approximately 0.1° for both alignment and beam noise (2σ). With a microwave system it may be possible to reduce both of these by a factor of 2 - although it will not be easy to maintain the alignment within an rms value of half a milliradian long term. However we can note that for landing guidance the angular accuracies required in elevation are not as great as those required from an upwind azimuth system sited on the longest runways.

In the Appendix A it has been seen that the beam noise tolerances for both localiser and glide path are relaxed at distances of a few miles from runway threshold. The tendency with modern VHF ILS is to regard this relaxation as unnecessary and there is probably no reason to specify anything other than the basic tolerances for a microwave system. However two points should be borne in mind. Firstly the signal to noise ratio will deteriorate more rapidly with range using microwaves since transmitter powers will tend to be tailored to the range required and propagation disturbances (e.g. Appendices B and C) may cause fading of intermittent loss of signal. Secondly the VHF ILS is a zero seeking guidance aid so the sensitivity variation across the beam is not of great importance (about 10% is asked for in practice) In the case of microwave position measurement it requires, ideally, uniform accuracy throughout the coverage and therefore tight control on sensitivity. In addition most systems will degrade in accuracy at large azimuth angles (at least 2:1 at angles $\pm 60^{\circ}$

from system centre) due to the sine of angle dependence and possibly due to data rate and dwell-time problems.

F.1.3 Airborne receiver accuracies

In addition to the ground system tolerances the errors introduced by the airborne equipment must be taken into account. In the case of VHF ILS accepted figures are 5 microamps for the glide path and 2.5 microamps for the localiser, corresponding to one sigma accuracies of 0.025 and 0.03° respectively. Whether these accuracies could be improved by use of a microwave system is debatable - bearing in mind that alignment accuracy will in many cases depend on the establishment in each aircraft of a 'zero' reference by means of a stable voltage or frequency.

F.1.4 Distance measurement accuracy

Distance information is provided by the ILS marker beacons and the 'gate' lengths for an aircraft approaching at 200 feet/second are about 600 feet for the inner, 1200 feet for the middle and 2400 feet for the outer marker positions. An alternative way of providing the distance information for approach and terminal area control is to locate an L band DME with the ILS and in this case the accuracy is within ±600 feet (1σ) (this is asked for in the medium range navigation role). If the approach and landing usage of DME is implemented then modern equipments could meet an accuracy specification of ±120 feet (1σ).

For a microwave system the accuracy required will vary greatly with the application. The justification of adding a C band DME to the aircraft in addition to the L band system already in use must depend on operational necessity. It will need to be shown that either the L band DME is restricted in deployment due to channel capacity or has insufficient accuracy for the operational uses envisaged. From consideration of bandwidth available at L band it can be inferred that a ten times increase in accuracy could be obtained at C band providing distance measurements within a 10-20 foot error envelope. However the bandwidth argument may lose its point if stable-time-frequency techniques are applied to the problem. There seems to be great scope for considering hybrid systems using a very low data rate interrogator-transponder to update a time-frequency measurement of distance[19].

F.2 Accuracy and the operational requirements

F.2.1 Approach and landing

The angular accuracies required of azimuth and elevation systems for landing - including automatic landing - are well established, and are covered

in previous sections. It remains to determine the DME accuracy required for (a) distance to threshold, (b) decision height measurement and (c) distance to go during roll out. We have seen that the markers have been used for (a) and therefore any DME, L band or C band would be more than adequate. For decision height measurement it is necessary to ascertain the height bracket within which the decision should be made. For Category II operations a figure of ±10 feet at 100 feet has been suggested as the size of this vertical gate. If this is taken as the two sigma limit then the DME inaccuracy should not be greater than 100 feet (1σ). (This allows for a smaller approximate 2 foot error contribution from the elevation measurement. If it were wished to keep the angular - and range contribution to height error equal then the DME accuracy would need to be improved to 40 feet.) For lower decision heights the DME accuracy should be improved in proportion. However below 50 feet the aircraft, whether CTOL or STOL will be over the runway so that height direct from a radar-altimeter would provide the simplest method of measurement. The roll out distance to go requirement has been variously stated. For safe and economic stopping a distance measuring accuracy of 100 feet would be sufficient but if distance to turn off is required then this may need to be improved to about 20 feet.

F.2.2 Flare guidance

If angle/DME computed flare is to be implemented then the permissible height errors should be comparable with those allowed from radio altimeters during autoflare, i.e. approximately 6 inches. Since the elevation subsystem must be set back beyond the touchdown point it requires a higher inherent accuracy than the normal glide path. At 50 feet height, above runway threshold, the elevation subsystem will be about 2000 feet away and will need an accuracy of 0.014° to contribute an error of 6 inches. Similarily a DME of accuracy 20 feet will also contribute a 6 inch height error. At lower heights during the flare the permissible height error will remain at about 6 inches so that the 0.014°/20 feet figures will give an improving performance.

F.2.3 Navigation and offset guidance

In Appendix E the equations for planar/conical xyz derivation are given. A study by Maths Department[20] is being carried out to examine the errors in x, y and z resulting from combinations of errors in the azimuth elevation and distance subsystems. It will be noted that in the general cases considered the individual xyz rms errors are compounded from R, θ and ϕ and that the position error will therefore generate a volume of uncertainty.

There are no stated requirements for future terminal area navigational accuracy using microwave guidance but it can be assumed that the performance required must be at least as good as the projected 1980 medium range navigational accuracy at the interface some 20-30 n miles from the airfield. It is assumed that in the time scale, 2 mile spacing using improved VOR/DME will be achieved implying an rms error of about 600 feet. This may also be improved by the increasing use of updated inertial and Doppler systems. We have seen that azimuth systems will have a worsening performance with increasing azimuth angle and at a range of 20-30 miles it is very likely that performance will be adversely affected by propagation. It can be seen therefore that a DME with 100 feet accuracy coupled with an azimuth system accuracy within 0.2^{o} will just about meet the 600 foot target.

In elevation the requirement is presumably to define height profiles with an accuracy at least equal to that achieved using barometric altimeters. This, in the height brackets applicable, means the accuracy should be better than 100 foot rms[2] calling for an operationally achieved elevation accuracy within 0.03^{o} in conjunction with a 100 foot DME accuracy. Maintaining this accuracy out to 20-30 n miles may be impossible to achieve in practice since, apart from the basic engineering problems, the propagation disturbances - which will include bending due to atmospheric refraction[13] - could degrade the instrumental performance by 2 to 3 times. A graph (Fig.34) taken from Ref.13 shows the extent of bending that will occur for a refractive index gradient of 120 N units/kilometres - a figure that will occur in most of the world for more than 5% of the time.

F.2.4 Offset guidance

At large azimuth angles - or in the case of guidance systems offset in azimuth to one side of a runway or pad - it is clear that the azimuth - or alignment accuracy becomes very dependent on the DME. In the extreme - if alignment for landing on an offset pad or runway is required than the DME error must not be greater than the required aligmment error. This may be only a few feet in some cases and is unlikely ever to be as gross as 100 feet.

F.2.5 Summary

It can be seen that the tolerances chosen for approach and landing are sufficiently good for the majority of the other operational requirements. However it is possible to identify a few areas of difficulty. Firstly a DME

accuracy of 100 feet would be sufficient for most applications but angle/DME flare and offset guidance will require 5 to 10 times improvement. In the case of the flare guidance the angular accuracy of the upwind elevation subsystem must also be inherently (about 2 times) better than the normally sited elevation unit. For three dimensional navigation the horizontal (xy) accuracy will match the medium range navigational accuracy at the limits of coverage (20-30 miles) and show a corresponding improvement at shorter ranges. The definition of height profiles will be limited by propagation and may only exceed the accuracy achieved by altimeters within a short range from the airfield (about 10 n miles).

Since both the flare guidance and the offset guidance have tended to be special aircraft or military requirements it would simplify equipment in Civil Aviation if the high accuracy DME were made a separate requirement - perhaps using the 15 Gc/s band. In the case of flare guidance this view is supported by the severe integrity problems that will be met in trying to use an all purpose DME.

A recent report by Hughes[21] has looked at the accuracy requirements of a microwave guidance system using terminal area separation standards as a criterion. The conclusions support the view that there are a small number of operational applications which would require an excessively high distance measuring accuracy and that for vertical profile control the elevation accuracy required is much higher than that required for approach and landing alone. However these extreme accuracies may not be achievable in practice so that it maybe necessary to recognise the limitations and plan the operations accordingly.

Appendix G

A COMPARISON OF PLANAR/CONICAL GLIDE PATHS

G.1 Geometrical differences and siting implications

The main differences between conical and planar systems have been examined in Appendices D and E. It will be seen that an advantage of the planar geometry lies in the elevation application where, for aircraft coupling to a glide path angle, the angular origin remains constant, irrespective of the offset distance of the subsystem from the runway centre line. The conical geometry used in a similar manner produces a hyperbolic path at low heights dependent on the off-set distance of the subsystem. It is important to consider the significance of these differences with respect to their effect on approach and landing.

Fig.30 shows the planar 3° and 6° paths - for any subsystem offset distance from runway centre line - compared with the glide paths resulting from a conical system sited at the same angular origin but at offset distances of 500 feet and 300 feet. In practice it is necessary to standardise on a crossing height above runway threshold and also to take into account the height of the system origin above ground. It can be seen from Fig.30 that the conical systems need to have their origin moved closer to runway threshold than for a planar system to achieve a specified glide path angle and threshold crossing height. In Fig.31 the changes of origin have been made and this demonstrates that in the case of the 3° paths there is negligible difference between the planar and conical paths down to 50 feet height, (graph D, Fig.31). For the same origin, offset distance, and a 6° angle the difference is increased to about 18 feet at 50 feet height and it should be noted that the threshold crossing height for both conical and planar is 90 rather than 100 feet. For STOL work however it can be expected that the elevation subsystem will be smaller in overall height and therefore could be sited closer to the runway. The change to a 300 feet offset (Fig.31) and a required 6°, 100 feet threshold crossing height results in the difference being reduced to about 3 feet at 50 feet height.

In practical installations of all types the subsystem position will need to be adjusted to allow for the height above ground of the physical centre of the elevation subsystem. This may be about 10 feet in the case of the CTOL 3° systems and 5 feet for the STOL 6°, and will require a corresponding adjustment of the subsystem longitudinal position with respect to threshold. This has been allowed for in Fig.31.

A further factor to be taken into account is the azimuth-elevation cross coupling that will occur at low heights on a conical system used as an angular guide beam. It can be seen that during the descent an aircraft movement to the left will result in a sink to a lower height whilst a movement to the right will cause the aircraft to rise. The magnitude of these effects is shown in Fig.32. The change in height with respect to the nominal glide path has been calculated for a 100 feet left and 100 feet right displacement of the aircraft. The cross coupling is small for the 3° case (less than 2.5% down to 50 feet) and rises to about 6% at 50 feet for the 6° path. It will be necessary to determine the significance of these terms with respect to automatic flight control, but a preliminary assessment indicates that the effect is negligible in the 3° case.

G.2 Tilted axis conical systems

It will be realised that all conical systems have one axis of planar symmetry; in the elevation systems this is in the xy plane which we have assumed to be at zero degrees of elevation. We could however tilt this plane to say 3° and compute all trajectories with respect to this new surface. This will then have the effect of virtually eliminating the conical geometry effects of 3° glide paths - and reducing the 6° path distortions down to the previously calculated 3° values. In fact if the angle of tilt of the xy plane were coded onto the transmissions then the system could be adjusted to give the optimum glide path for the runway - and still allow the computation of three dimensional tracks or derivation of height profiles.

There has been talk of multiple glide paths into a runway - and air selectable paths in aircraft. Some caution should be exercised for the following reasons. Firstly in the case of aircraft there will usually be a preferred glide path angle dependent on its performance characteristics and aircrew training. In this context cockpit selection of glide path sounds, instinctively, unsafe in terms of this type of operation. In the case of the runway the feasibility of using multiple glide paths for landing can also be questioned. The ATC problems would be increased, and there would be great difficulties with approach lighting patterns and Vasi's - which normally have a narrow field of view. It has been pointed out that runway crossing height and touchdown point are important parameters to standardise and this can in general only be accomplished at one setting of the glide path. As well as these considerations the effects of trailing vortices would also need to be examined since it would appear that the safe distance between an aircraft on a high angle and one on a low angle would need to be increased.

G.3 Summary

It should be emphasised that conical systems, correctly used to measure height present no problems and therefore no difficulty should arise with systems which include the DME. For defining a glide path angle, the problems that arise are amenable to solution so long as due care is paid to positioning the subsystem. In addition consideration should be given to tilting the xy plane since this would virtually eliminate any difficulties. However it should be stressed that most of the operations envisaged on these simple angular paths will of necessity require visual monitoring of the landings so that the profiles at very low heights will have little operational significance. In the case of flare out one can superimpose typical flare profiles on the graphs of Fig.31 and from this it is immediately obvious that neither the conical or the planar paths are suitable when used alone. There is therefore no alternative for automatic landings to the use of a separate flare guidance system such as the radio-altimeter or proposed supplementary angle - DME system.

Table 1

COMPARISON OF GUIDANCE AND POSITION MEASUREMENT APPLIED TO AIRCRAFT APPROACH AND LANDING

	Guidance	Position measuring (navigation)
Primary purpose	To guide an aircraft along preset straight tracks giving a near optimum profile for a safe landing.	To provide position information from which straight or curved three dimensional flight paths maybe computed relative to a desired track or landing point.
Extensions of use	To provide fixed non-linear guidance as alternatives to straight line approach and overshoot paths.	To supply aircraft position and track information to ATC for monitoring of separation and sequencing.
Aircraft instrumentation	Ground referenced zero-seeking receivers feeding flight directors and AFCS.	Ground and airborne referenced position co-ordinate measuring systems feeding computer relating present position to required (maybe stored) track. Processed information fed to flight directors and situation displays as well as AFCS.
Pilot monitoring	Monitoring task is simplified by standardised and non-complex flight path. Normal flight instruments giving height, rate of descent, aircraft attitude, air speed etc. Note that 'distance' or 'actual position' information is not essential.	Situation display giving actual track relative to desired track is essential in addition to normal flight instruments, directors, AFCS. Situation relative to other aircraft maybe desirable. Similarly time lost or gained indicator maybe essential.
Information received	Azimuth and elevation angle from preset datums. Distance indication (markers). Runway identification.	Azimuth and elevation position computed from direction cosines or angle and distance from origin. Distance information continuous throughout coverage. Runway identification and data channels for:- airport status, position co-ordinates of ground equipment, obstacle clearance information.

Table 1 (Contd)

	Guidance	Position measuring (navigation)
Performance	Coverage maybe limited to fairly narrow approach and departure sectors (e.g. $\pm 30^{\circ}$ to 15 n miles). Highest accuracy needed only near to guidance datums (e.g. total alignment accuracy $\approx$ 1 milliradian. Sensitivity tolerance 10%).	Coverage ideally 360° and, over at least some sectors, a range of 30 n miles. Basic guidance accuracy (better than 0.1°) must be maintained throughout coverage.
Integrity and reliability	Ground and airborne equipment tailored specifically to the approach and landing function. Even so requires equipment redundancy and high degree of airborne and ground monitoring.	Ground and airborne equipment cover wide range of functions, will require redundancy and probably special integrity checks. For example, the selection and display of wanted flight profile which maybe from ground or airborne computer store. IMC operations will need ATC monitoring to comparable accuracy and similarly the pilot will need high integrity information and displays if he is to emulate VFR operations in IMC.

SYMBOLS

a	$\left(\frac{4\delta}{\lambda}\right)^{\frac{1}{2}}$ path difference parameter equation (B-1)
$C(a)$ and $S(a)$	Fresnel integrals equation (B-1)
d	distance along ground between transmitter and receiver (Fig.21)
d_1-d_7	distances defining subsystem positions relative to runway
E	error
E_R	received signal amplitude
h	height
h_1,h_2	height of aerial centres above ground
ℓ	polar diagram loss as a function of angle
L_d	loss due to diffraction
r	reflection coefficient
R	slant range measurement
t	time
x,y,z	the cartesian co-ordinates of aircraft position and the corresponding axes of the subsystems
α	crest angle subtended by a diffracting surface or edge to the transmitter
β	angle between direct raypath and reflected raypath leaving transmitter
γ	angle with respect to the horizontal of the direct ray between transmitter and receiver. Also depression angle Appendix B
δ	path difference between direct and reflected or refracted path
θ	azimuth angle measurement
θ_c,θ_p	as above for conical and planar systems
θ_{cy},θ_{cx}	azimuth angle measurements from orthogonal xy conical systems
ϕ,ϕ_c,ϕ_p	corresponding elevation measurements
ψ	phase angle change on reflection
ω	$2\pi f$ = angular frequency

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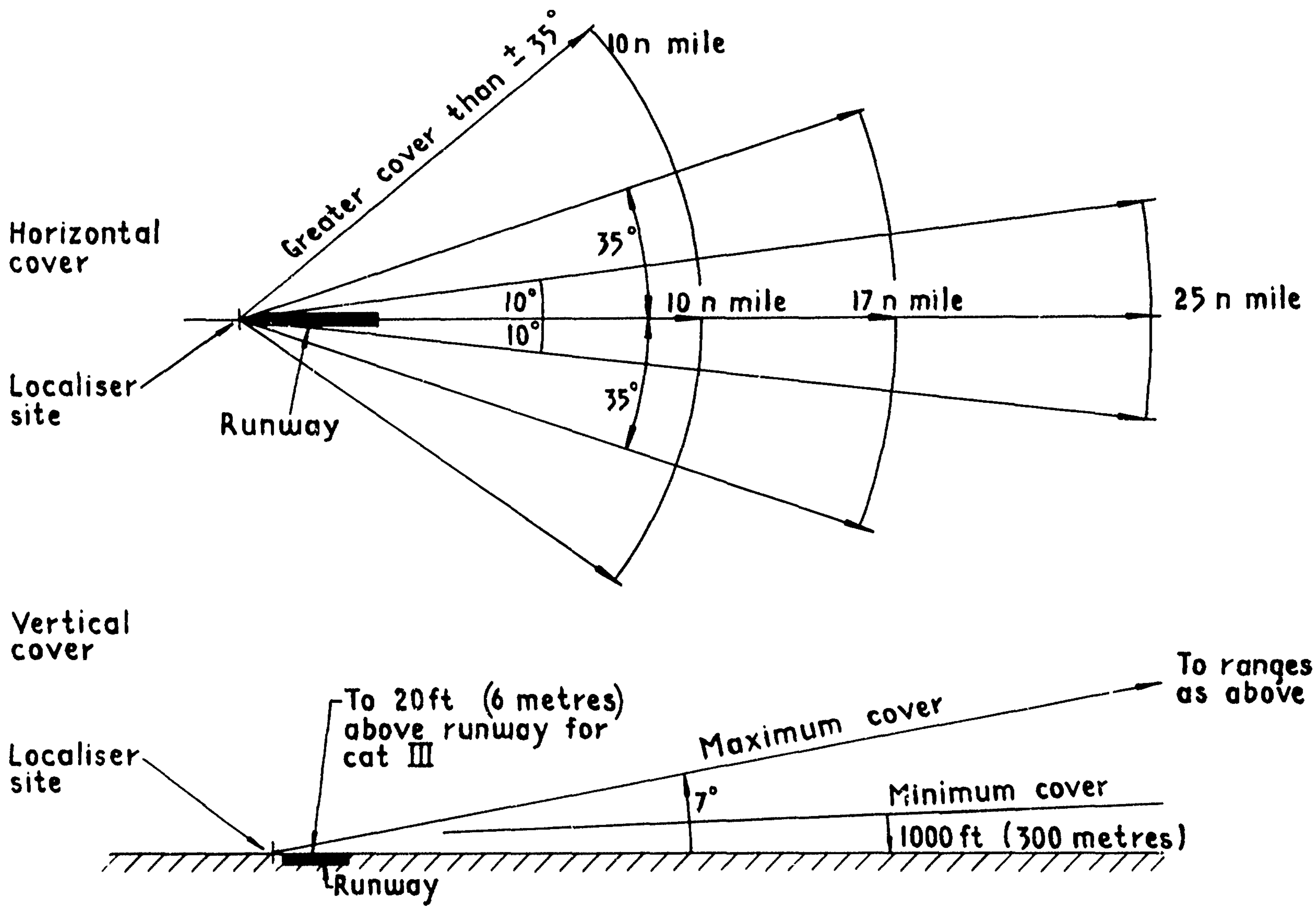


Fig.1 ICAO azimuth service (localiser) coverage

Fig.2

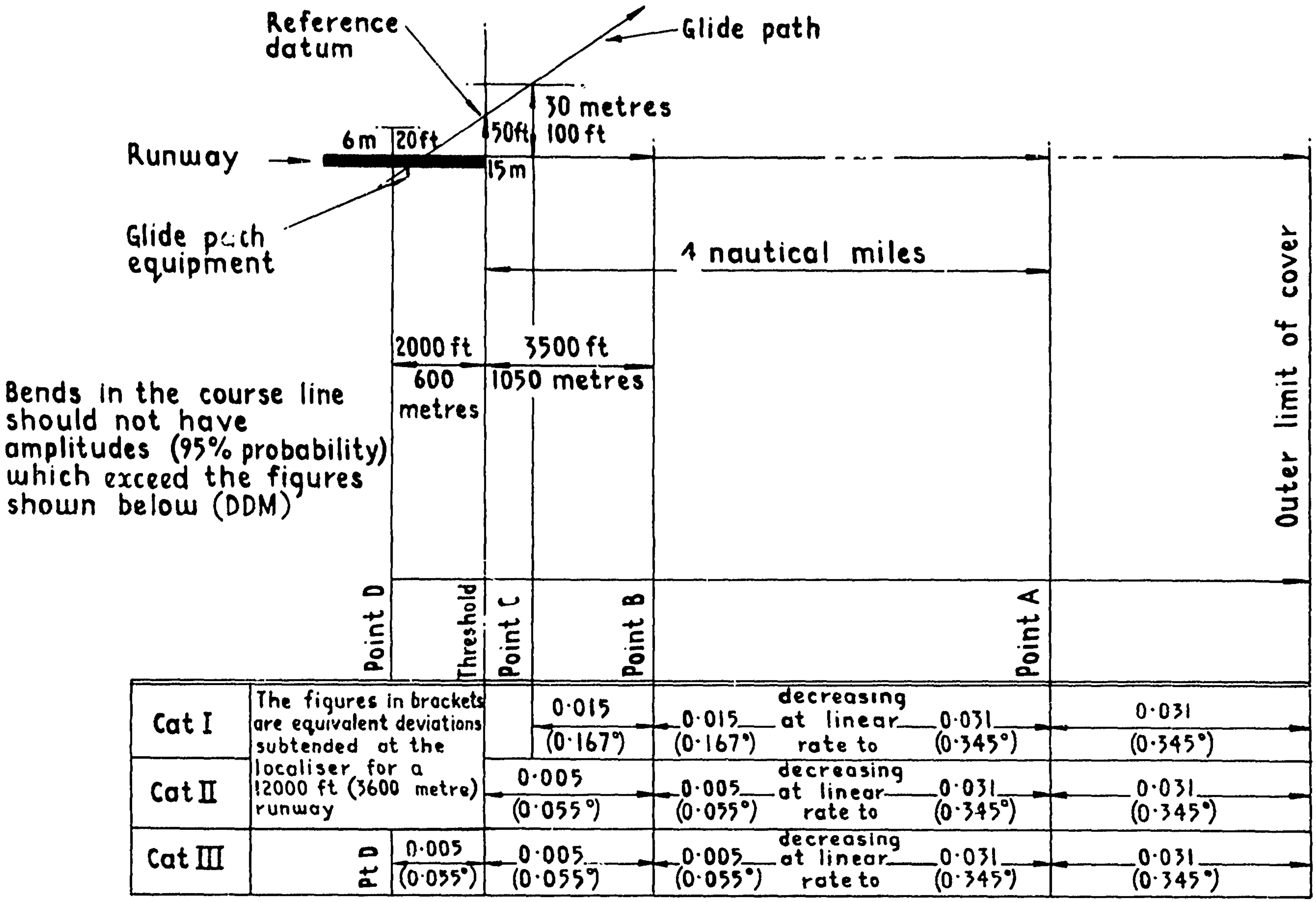
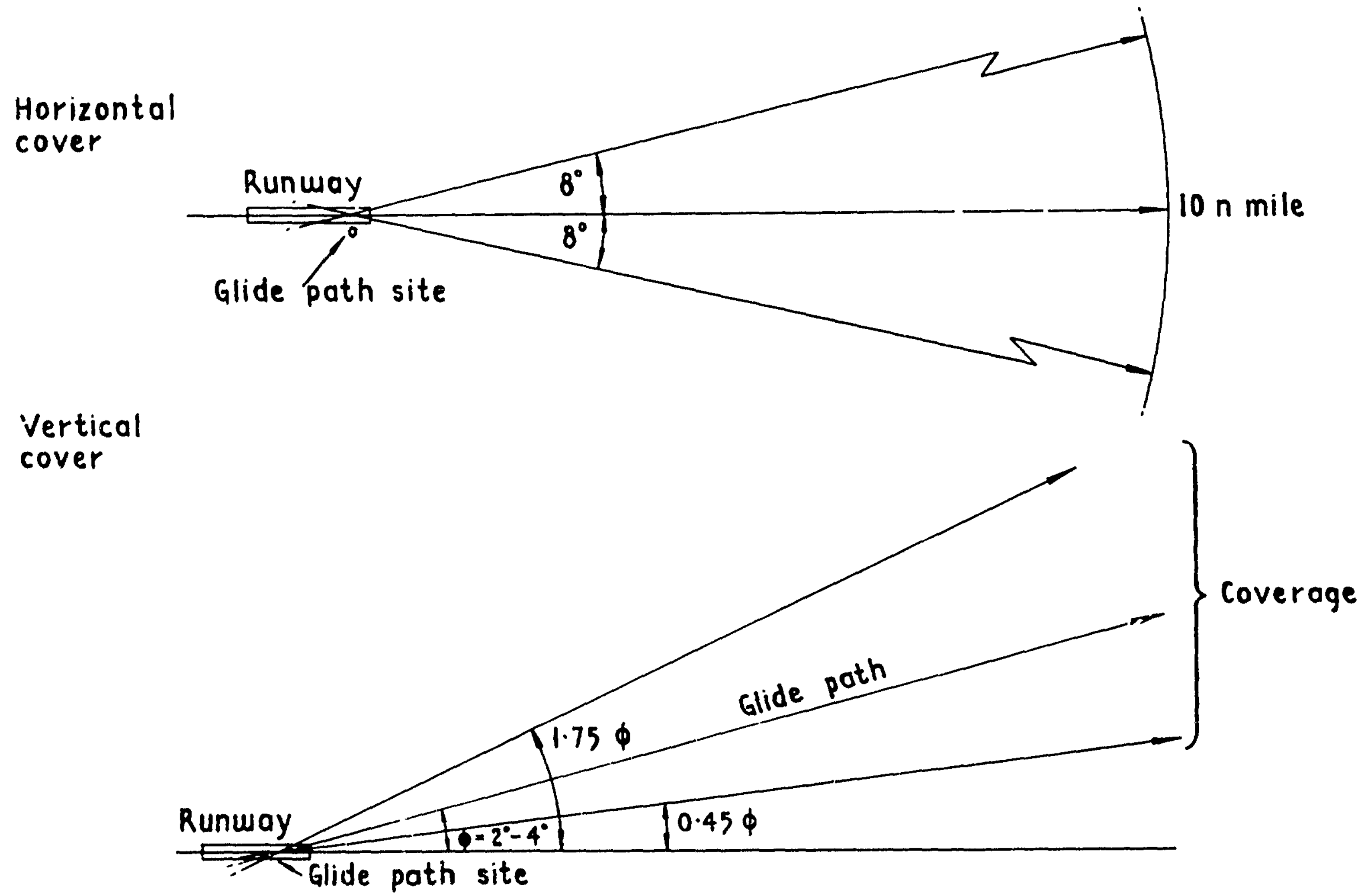
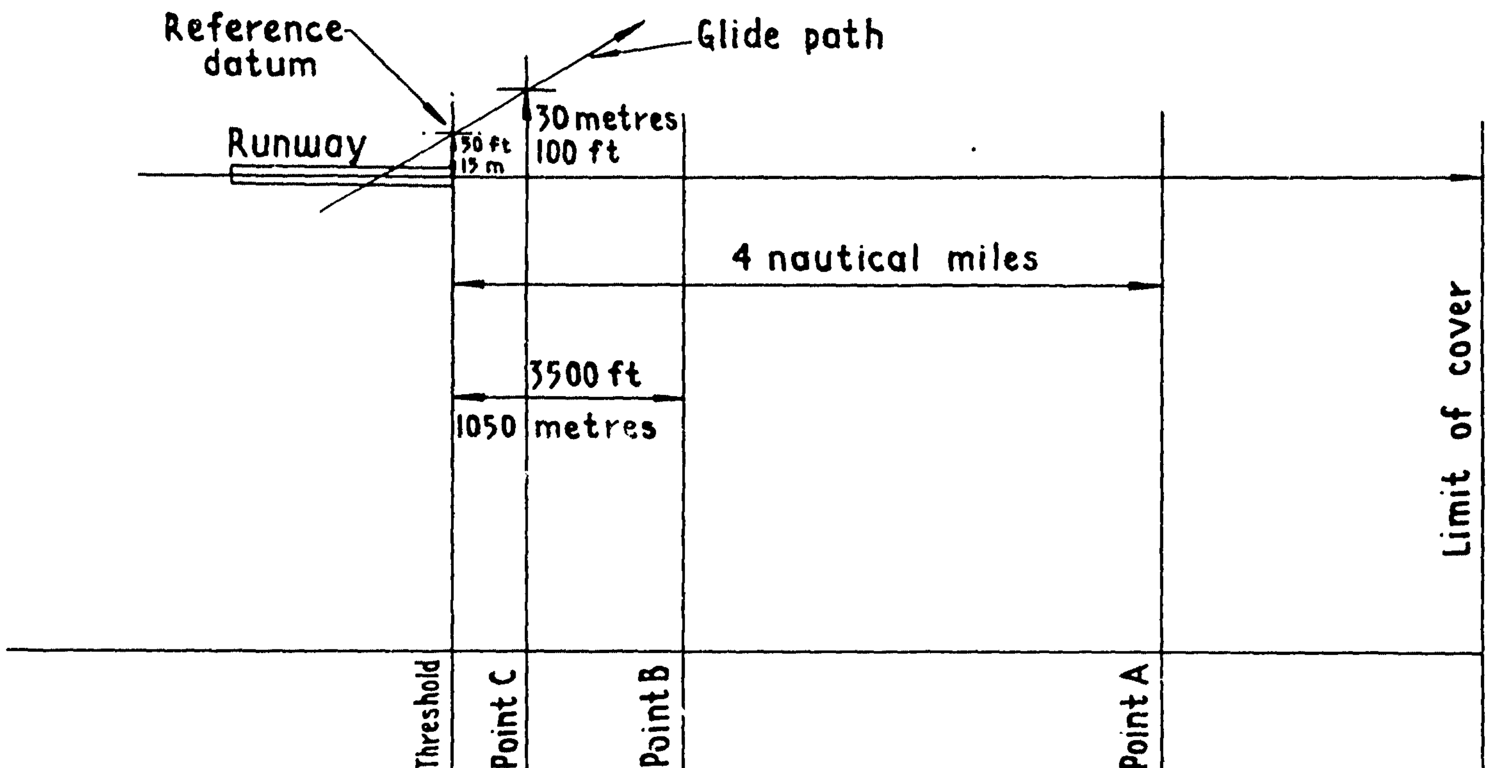


Fig.2 ICAO quality of azimuth signals



ϕ = Glide path angle adjustable between 2° and 4° with operationally preferred value of 2·5°

Fig.3 ICAO vertical service (glide path) coverage



		Threshold – Point C	Point C – Point B	Point B – Point A		Point A – Limit of cover
Cat I			0·035 (0·12°)			
Cat II	Figures in brackets are angular error limits at the preferred glide path angle of 2·5°	0·023 (0·0775°)	0·023 (0·0775°)	decreasing at linear rate	0·035 (0·12°)	0·035 (0·12°)
Cat III		0·023 (0·0775°)	0·023 (0·0775°)	decreasing at linear rate	0·035 (0·12°)	0·035 (0·12°)

Bends in the glide path should not have amplitudes (95% probability) which exceed the figures above (DDM)

Fig.4 ICAO quality of vertical signals (beam bends)

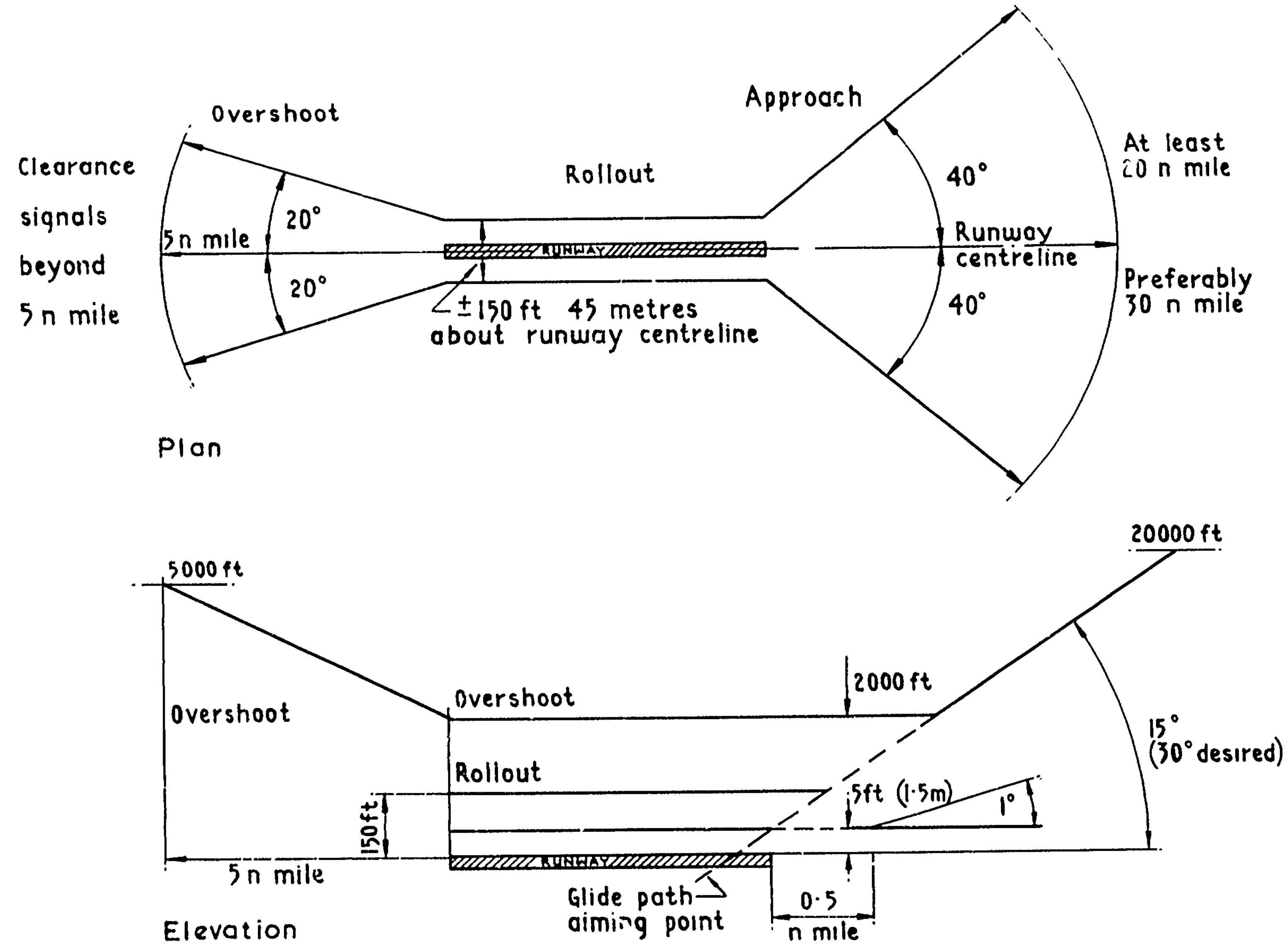


Fig.5 Future civil operational requirements (ICAO prov OR)

Fig.6

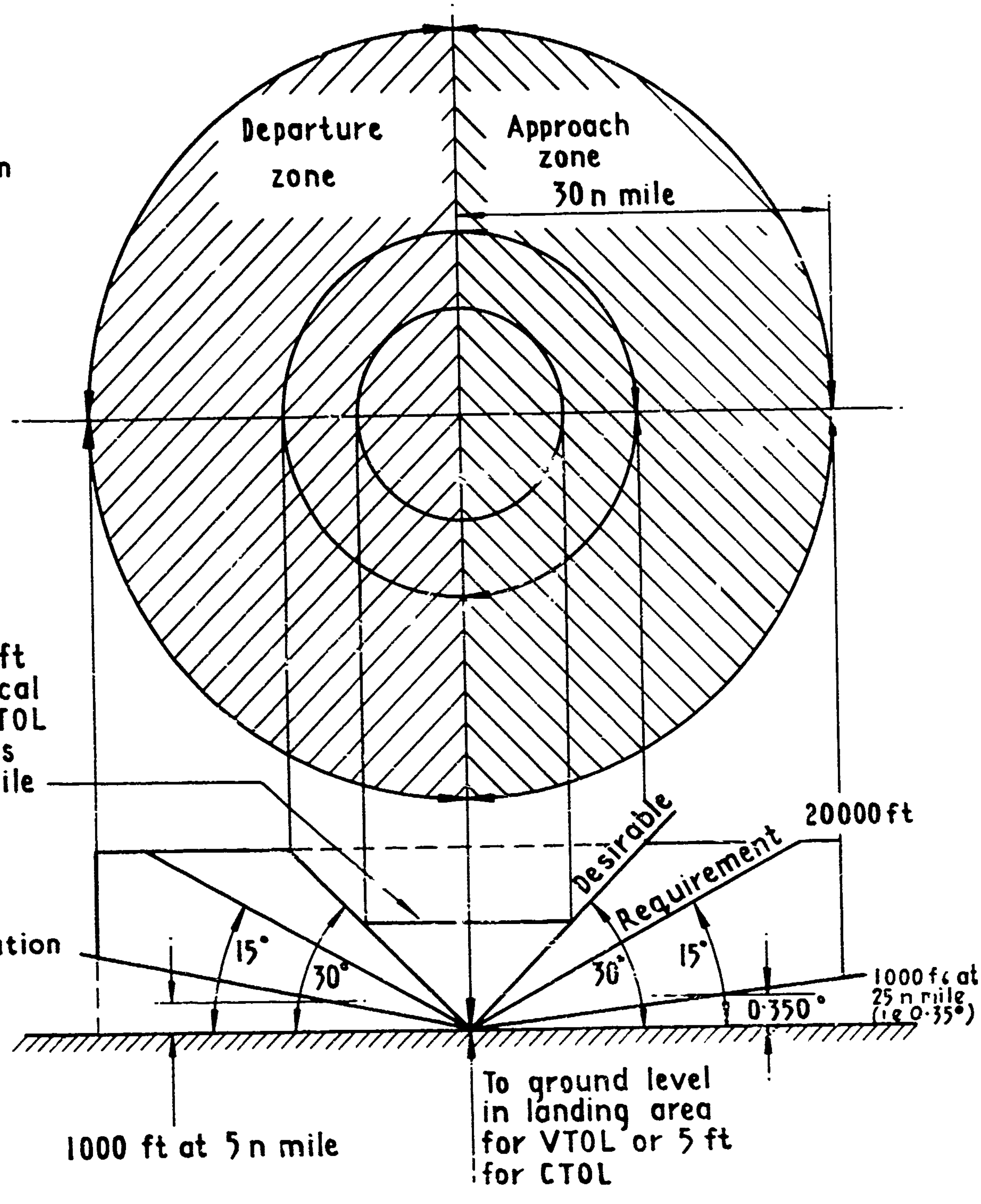


Fig.6 Overall volumetric coverage of the various OR's

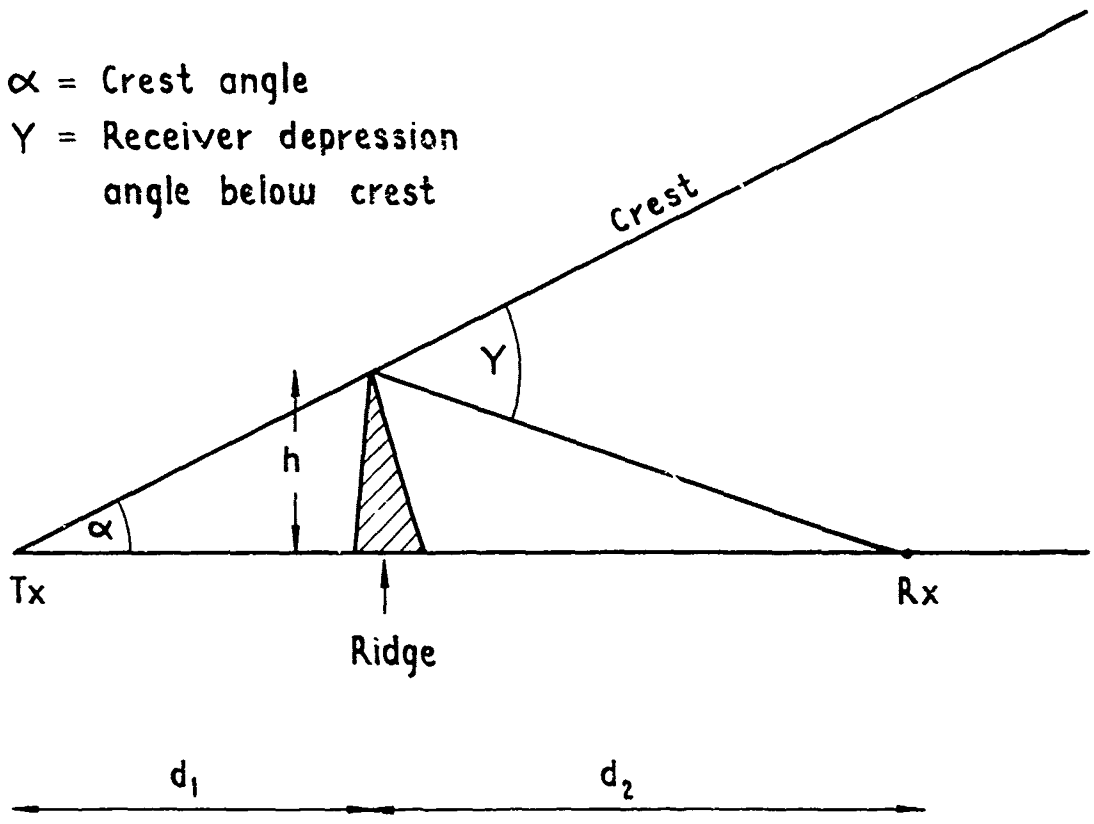


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Fig.7 Knife edge diffraction geometry

Fig.8

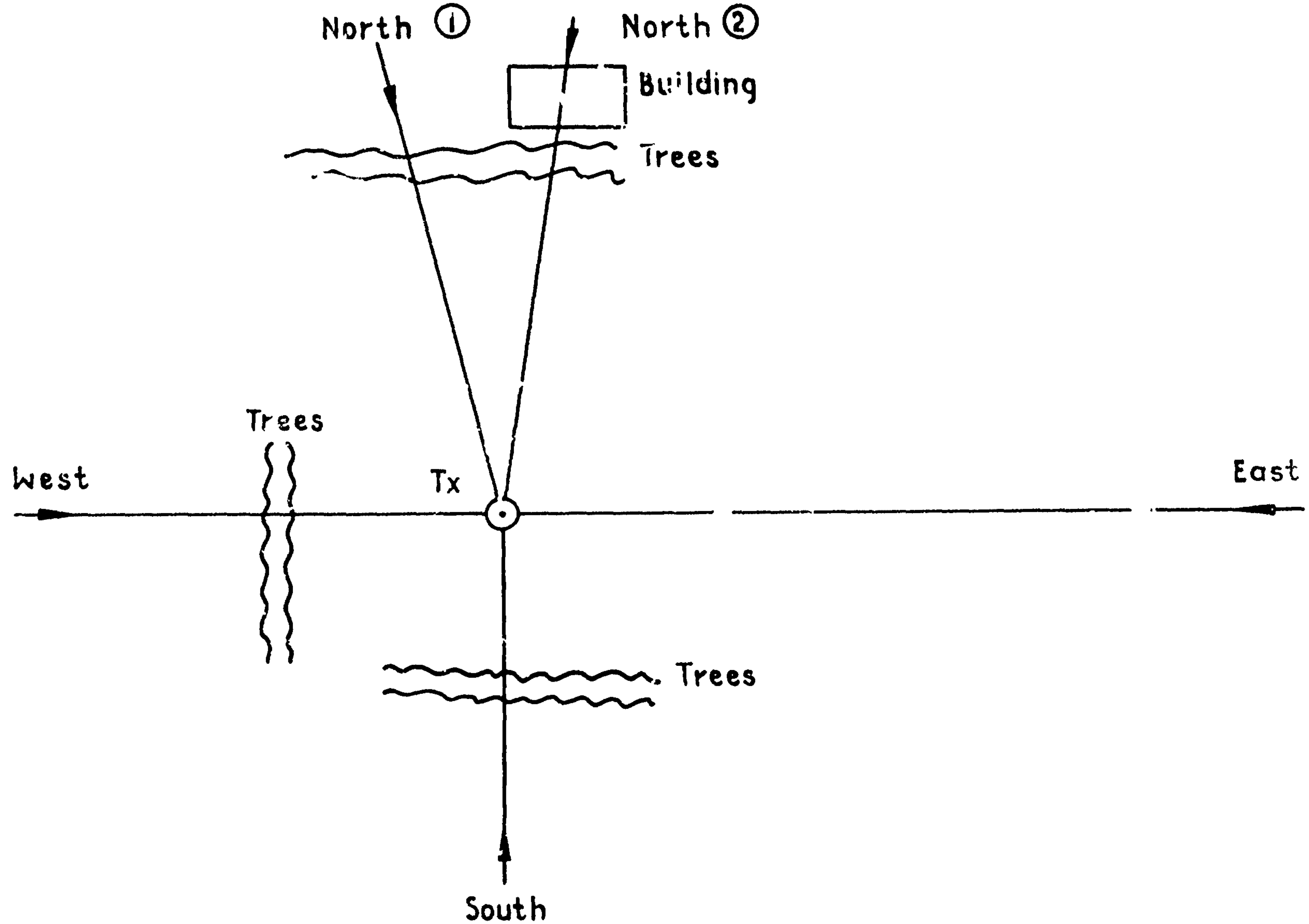
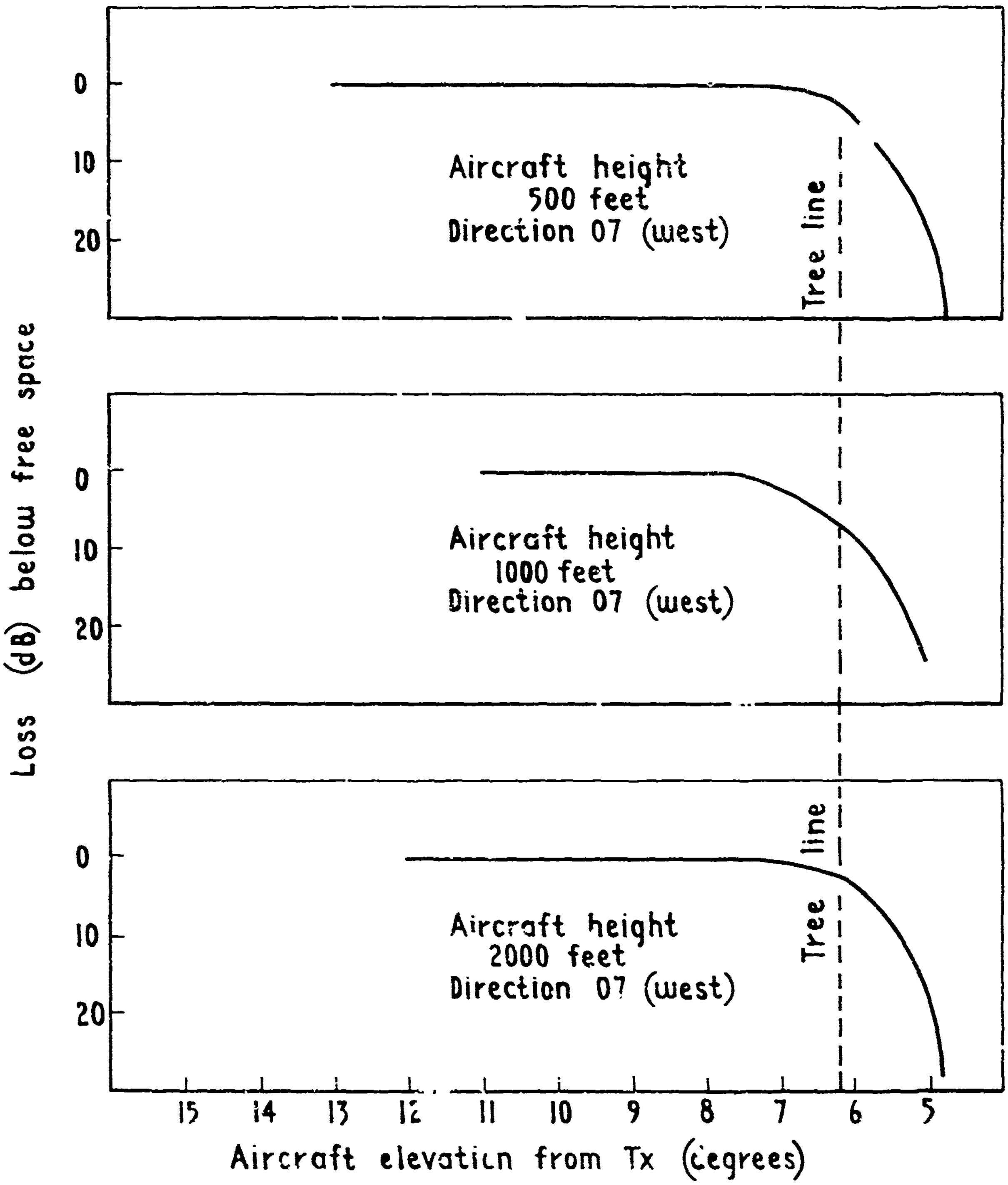


Fig 8 Experiment to determine shadowing loss due to trees



Horizontal polarisation
Tx aerial height 18 feet

Fig.9 Shadowing losses (HP)
west - Tx height 18 feet

Fig.10

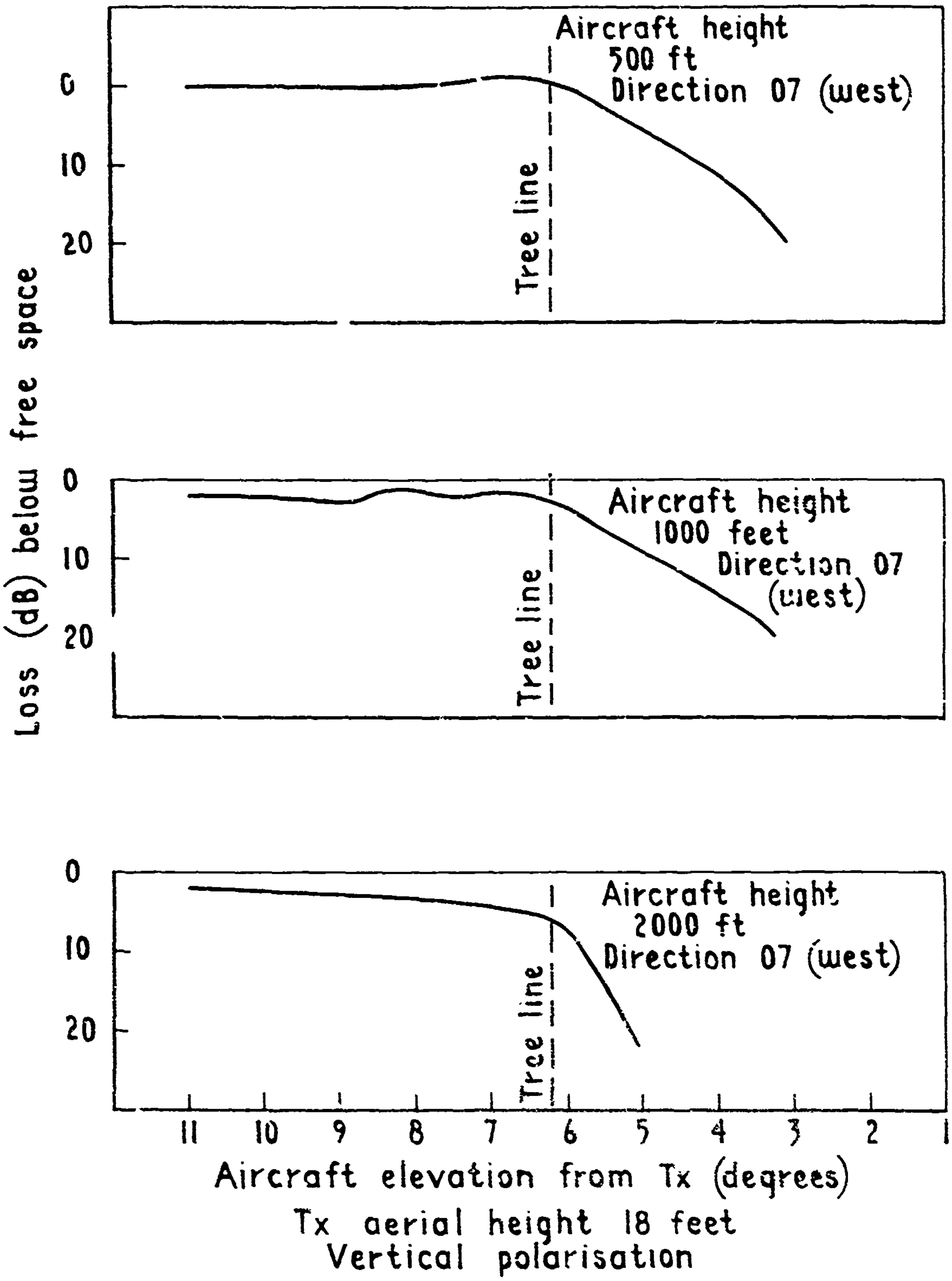


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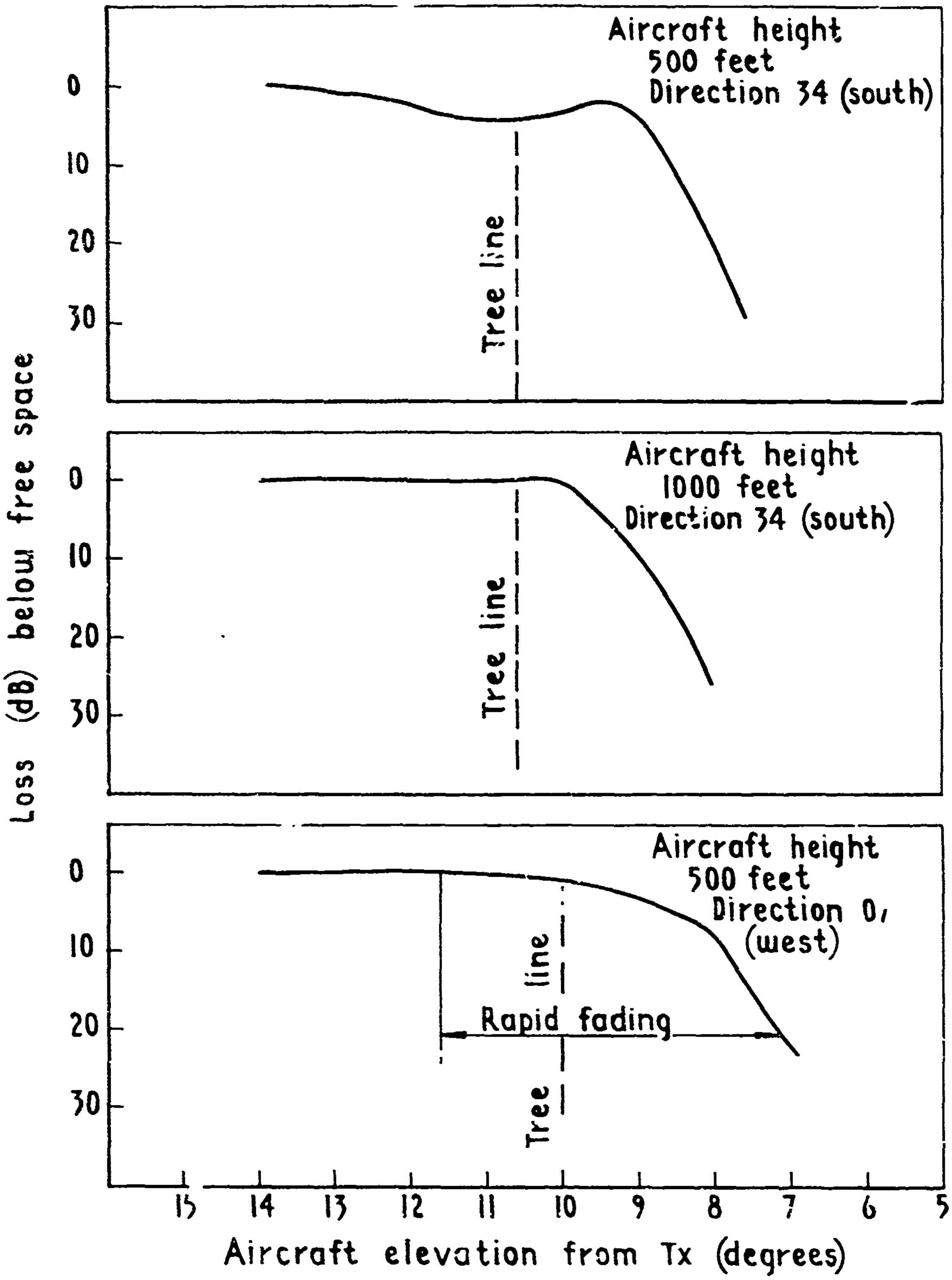
Fig.10 Shadowing losses (VP)
west Tx height 18 feet

008 %4099



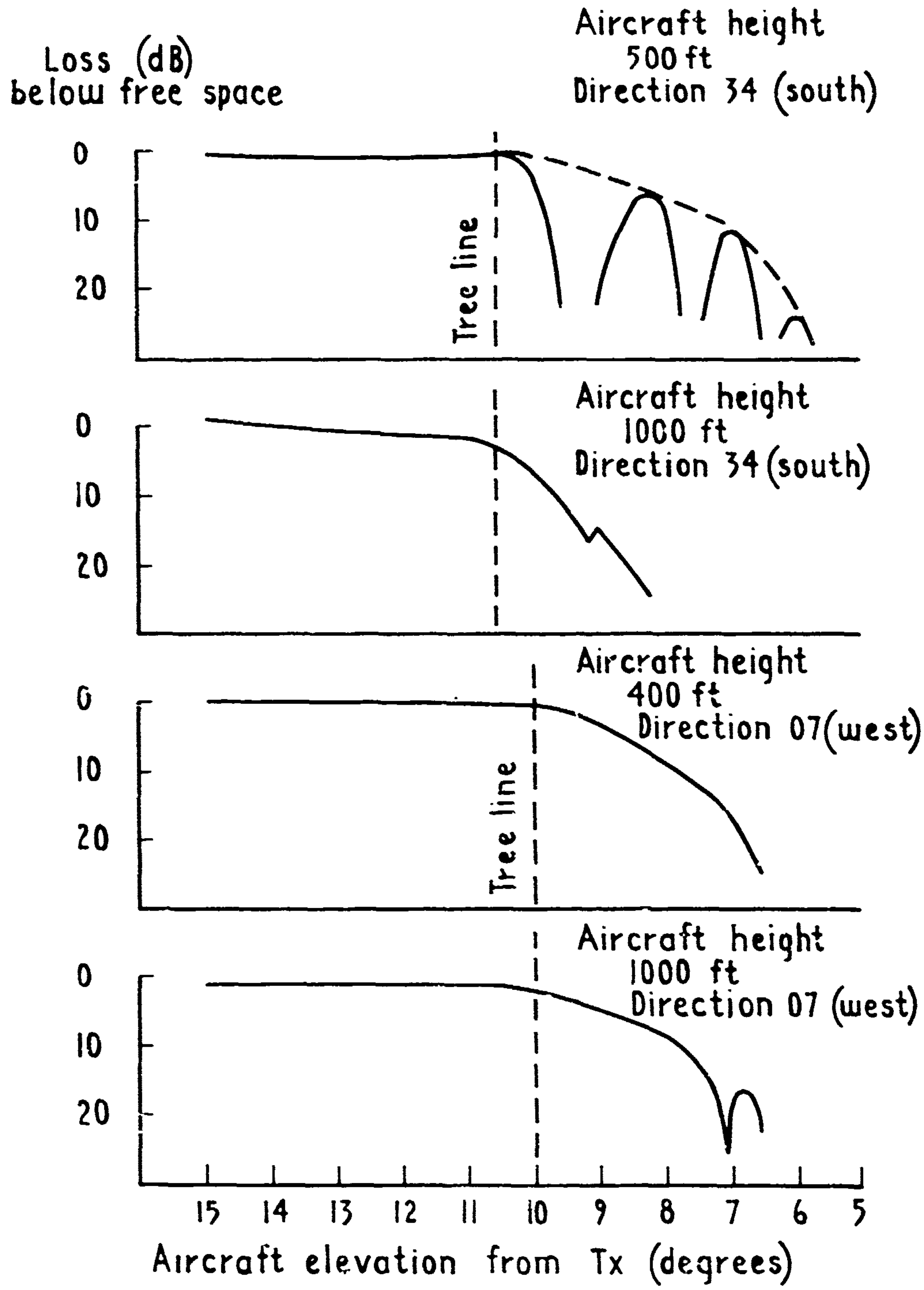
Vertical polarisation
Tx aerial height 5 feet

TR 71186

Fig.11 Shadowing losses (VP) south and west - Tx height 5 feet

904100

Fig.12

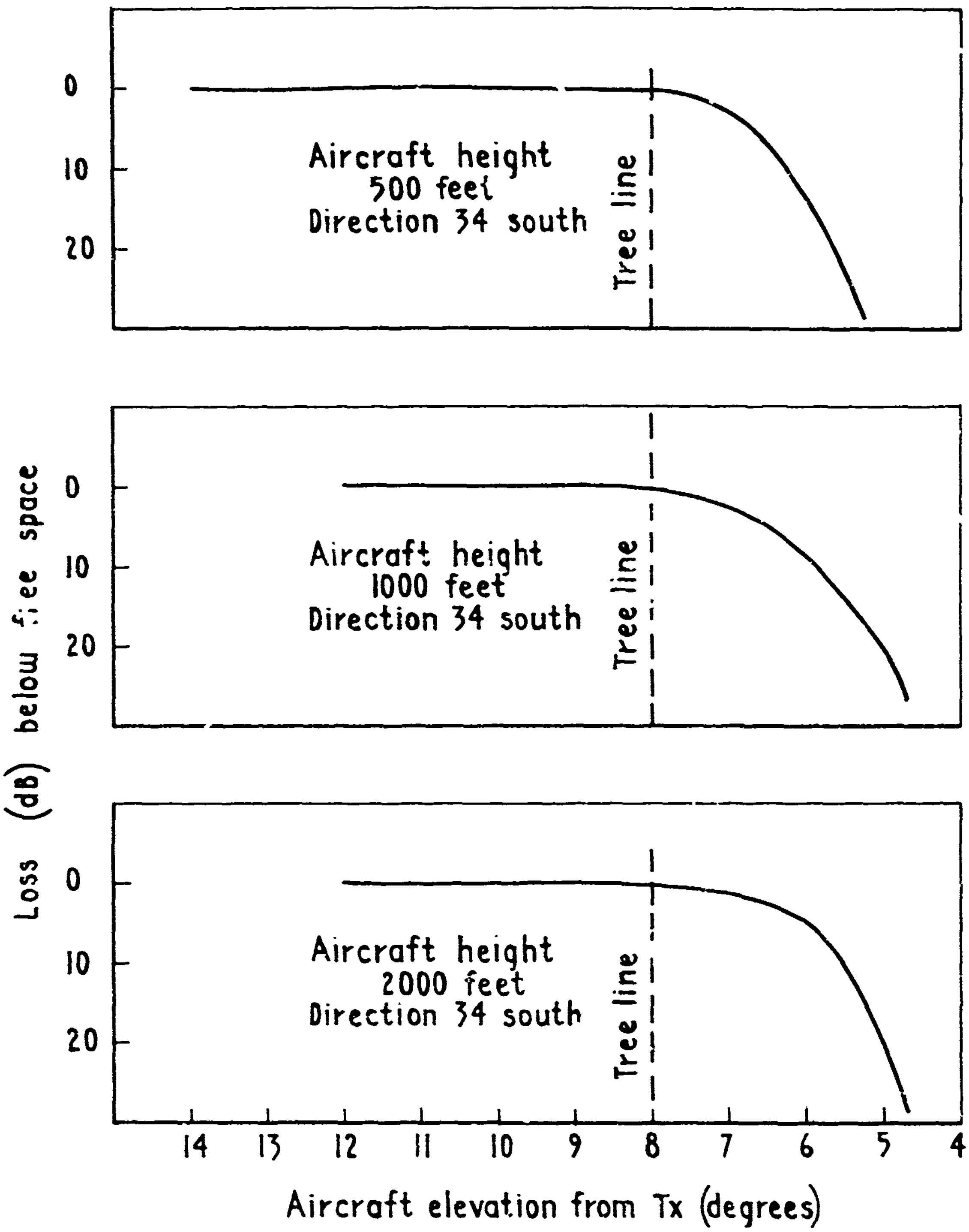


Horizontal polarisation
Tx aerial height 5 feet

Fig.12 Shadowing losses (HP)
south and west - Tx height 5'

TR 71186

008 904101



Horizontal polarisation
Tx aerial height 18 feet

Fig.13 Shadowing losses (HP)
south Tx height 18 feet

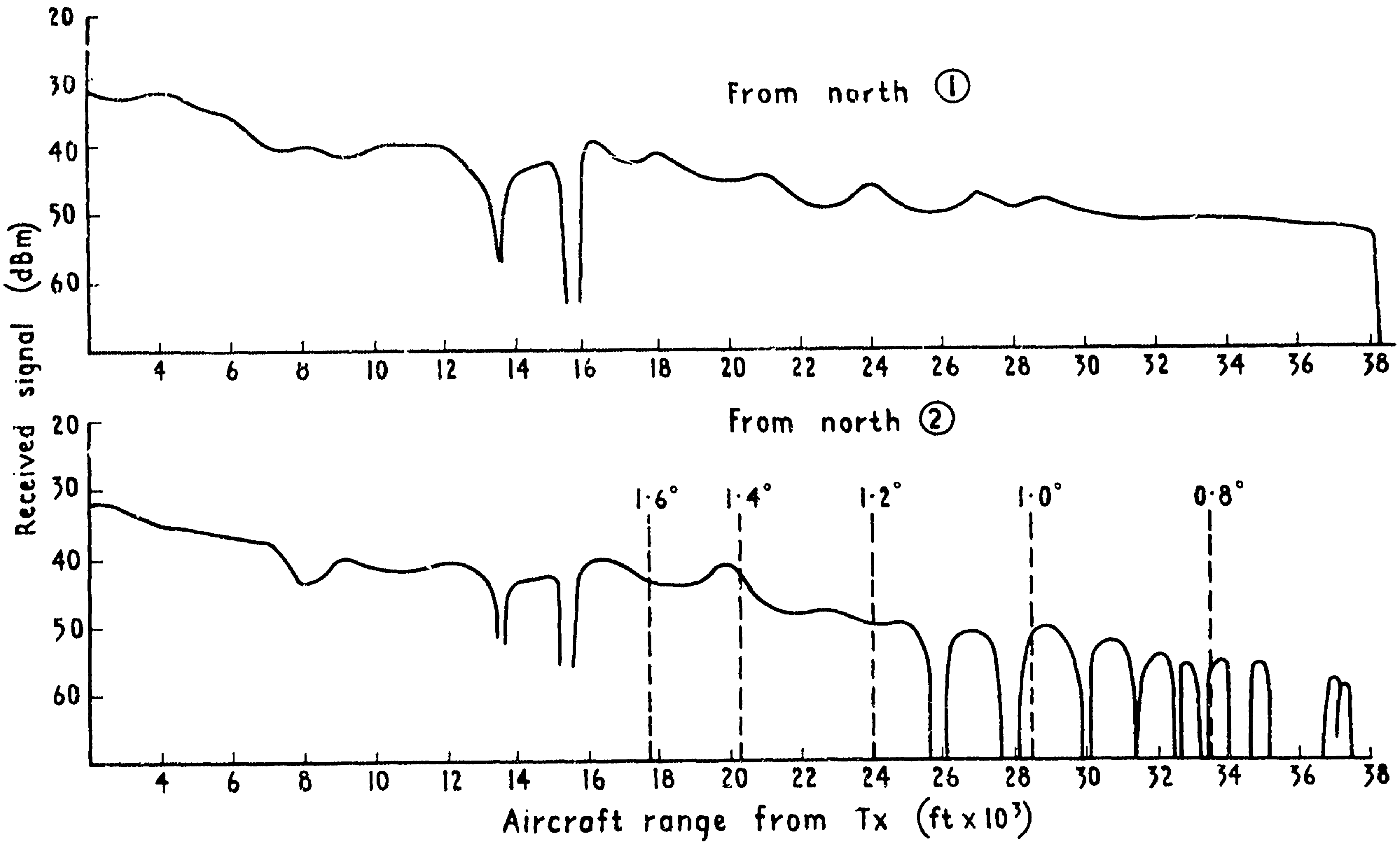


Fig.14 Comparison of signal profiles in north 1 and 2 directions

West

South

North 1 North 2

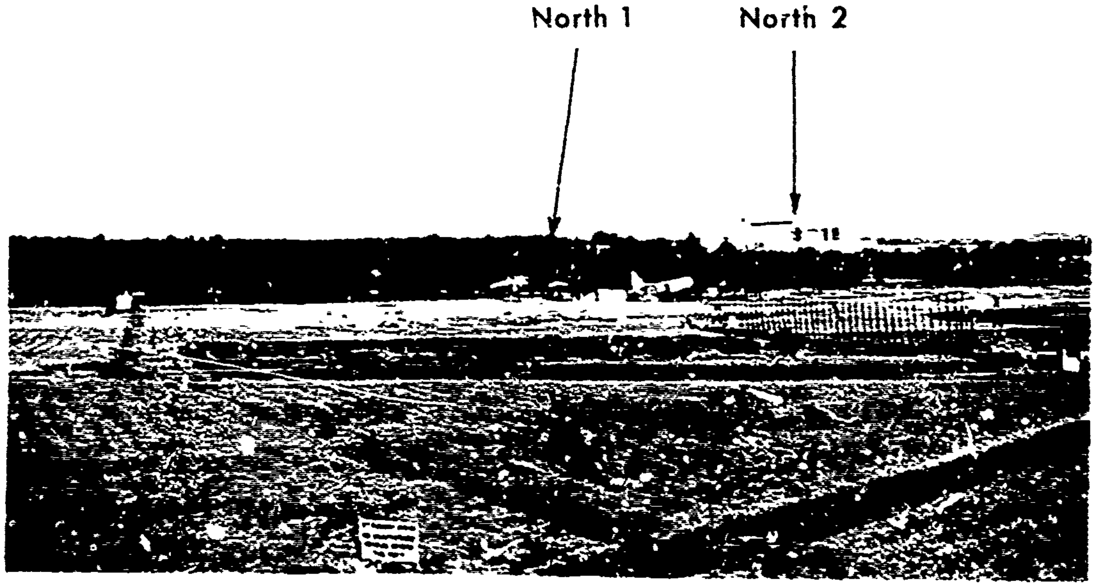


Fig.15. The South, West and North views from the transmitter

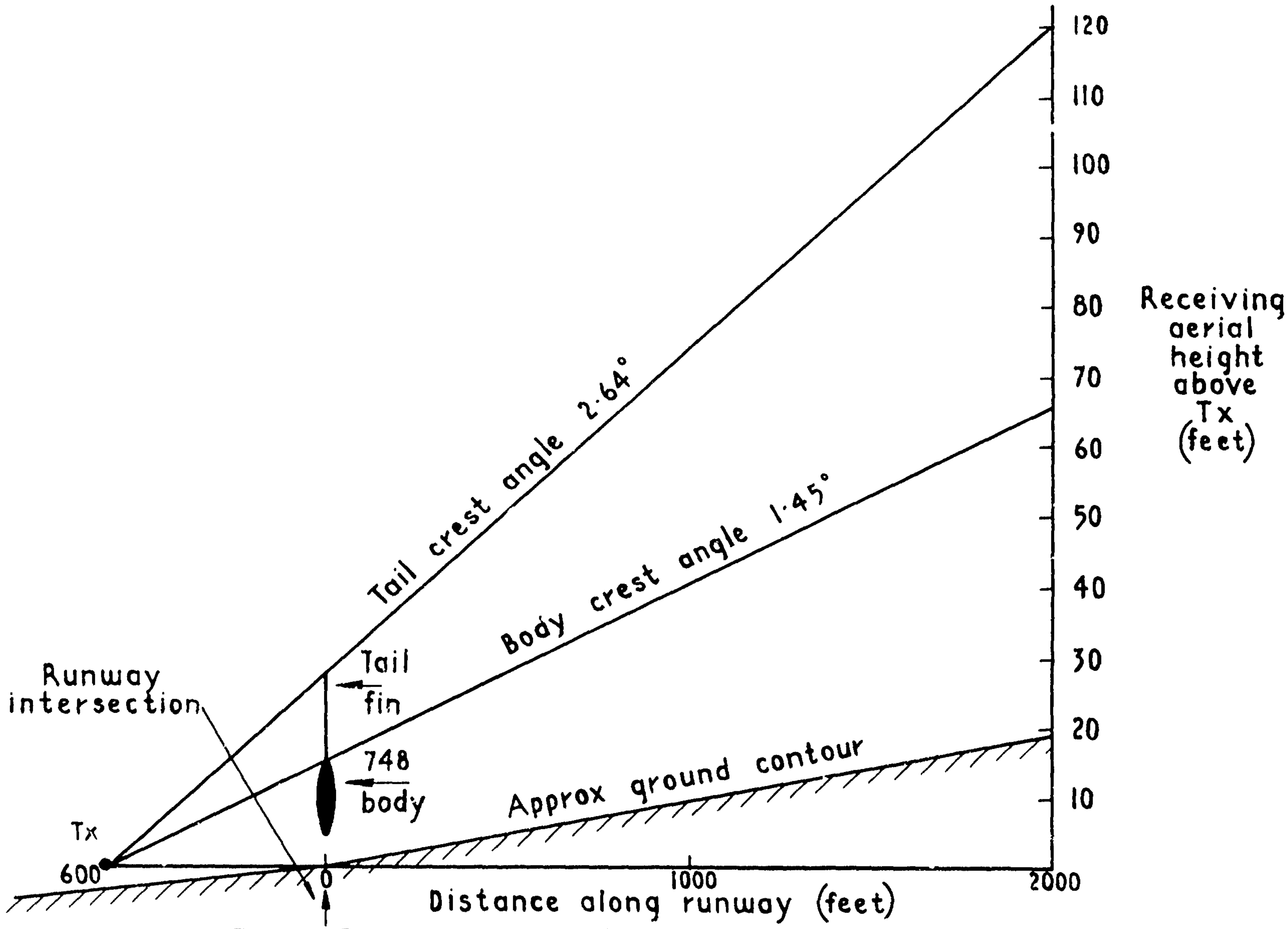


Fig.16 Geometry of HSA 748 shadowing experiment

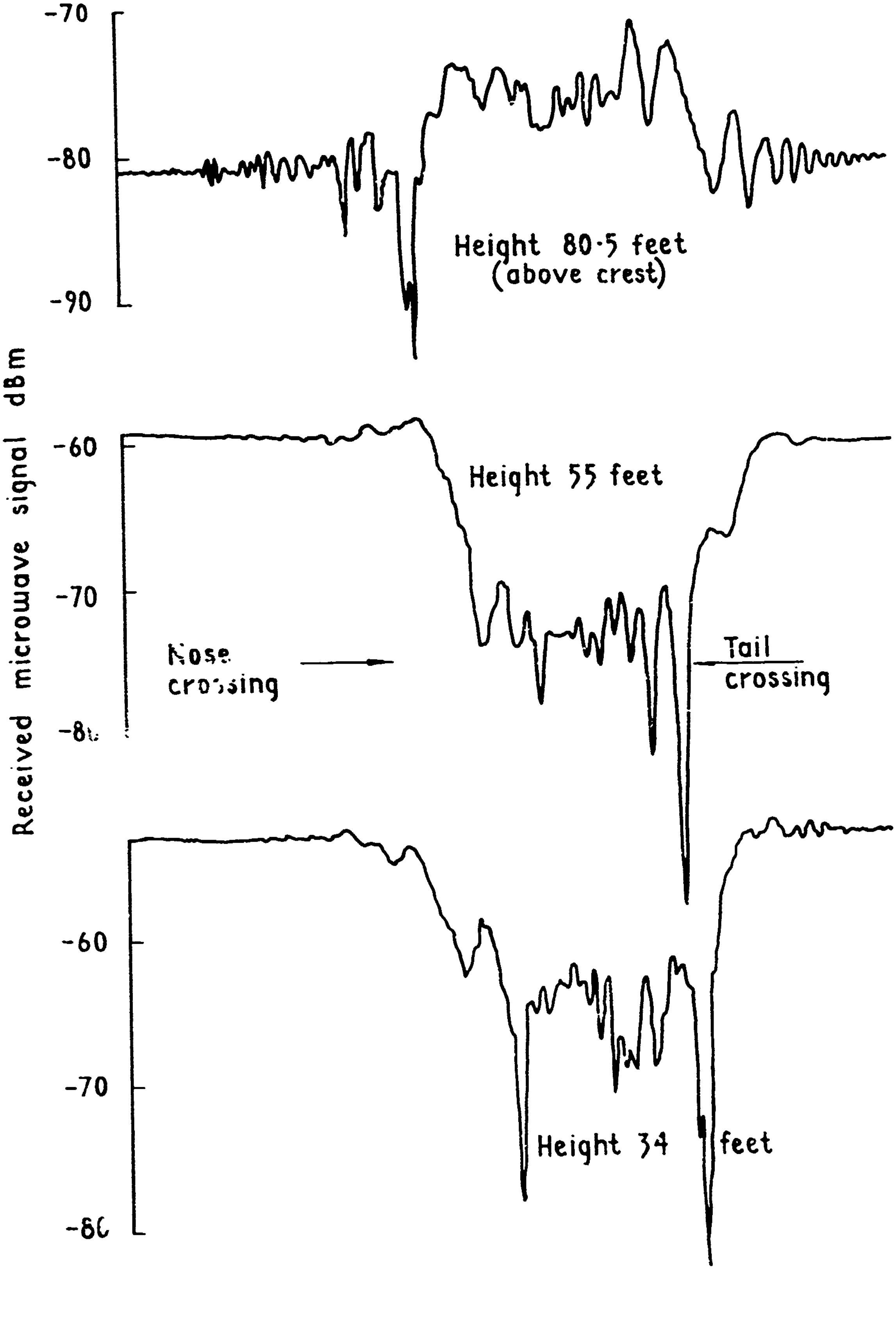


Fig 17 Recordings of shadowing loss from HSA 748

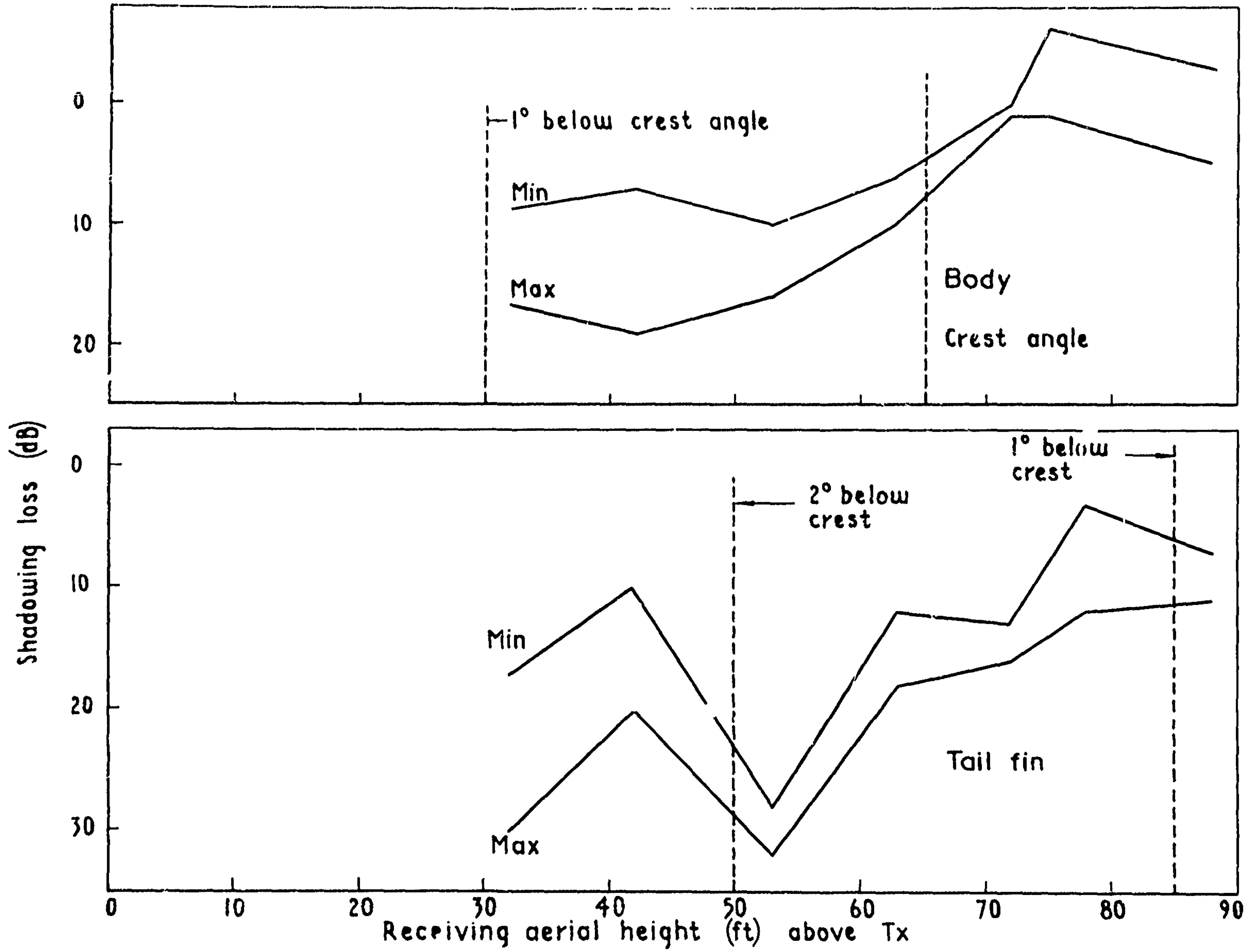


Fig.18 Envelope of losses due to body and tail fin

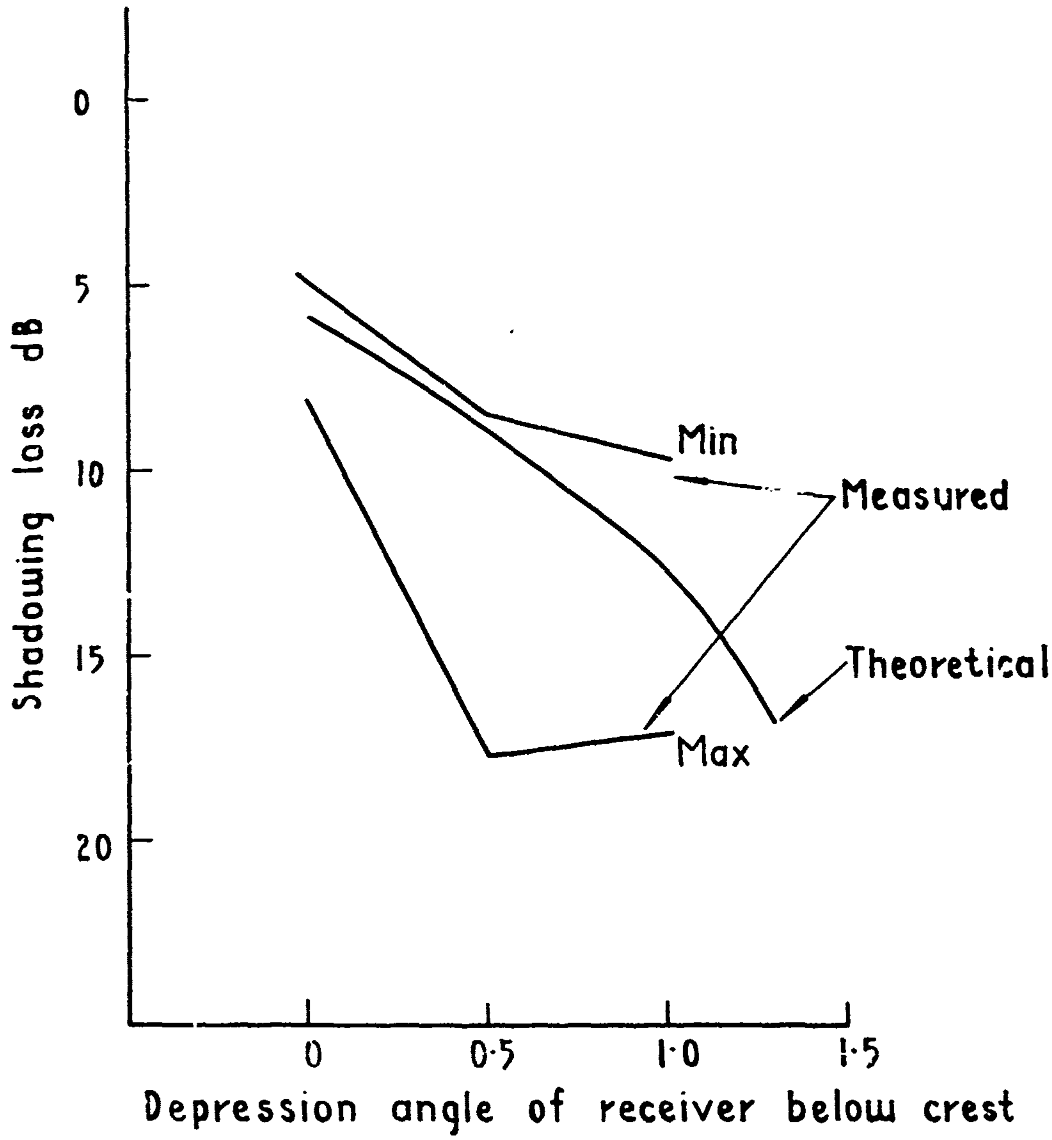


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Fig.19 Comparison of measured losses and knife edge theory

Fig.20

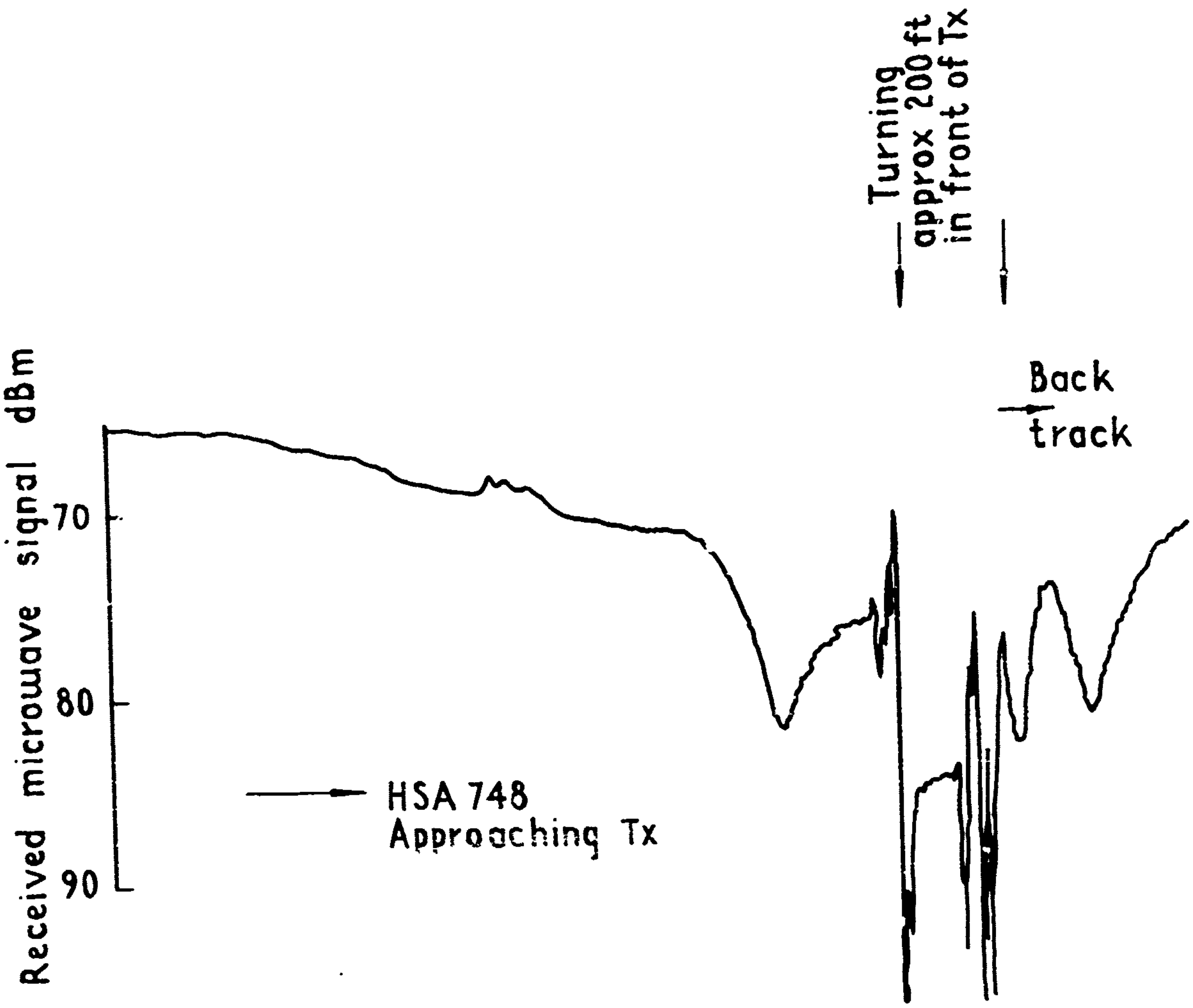

Fig.20 Recording taken of HSA 748 shadowing loss during centre line of runway roll

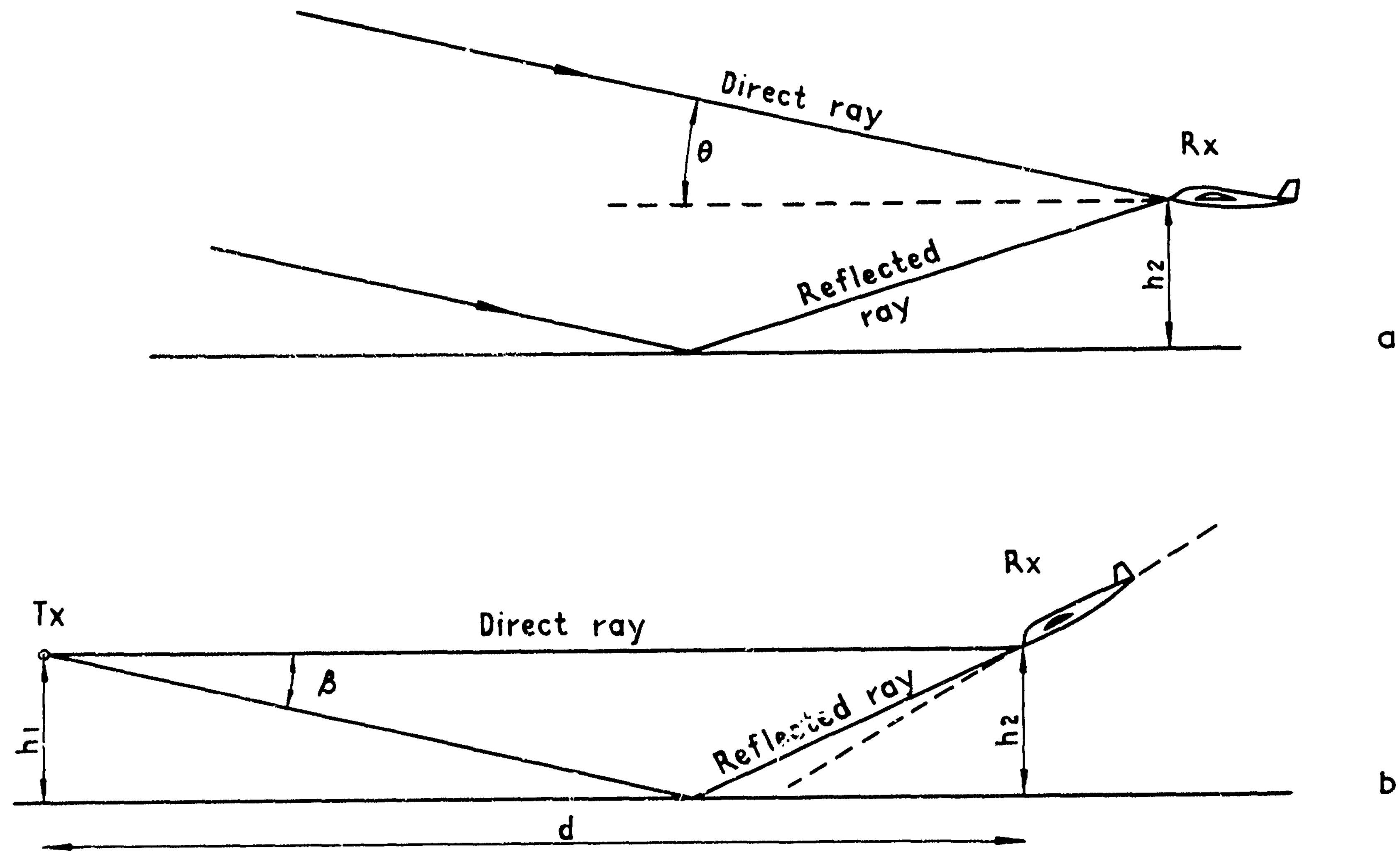

Fig.21 a & b Geometry of interference mechanisms

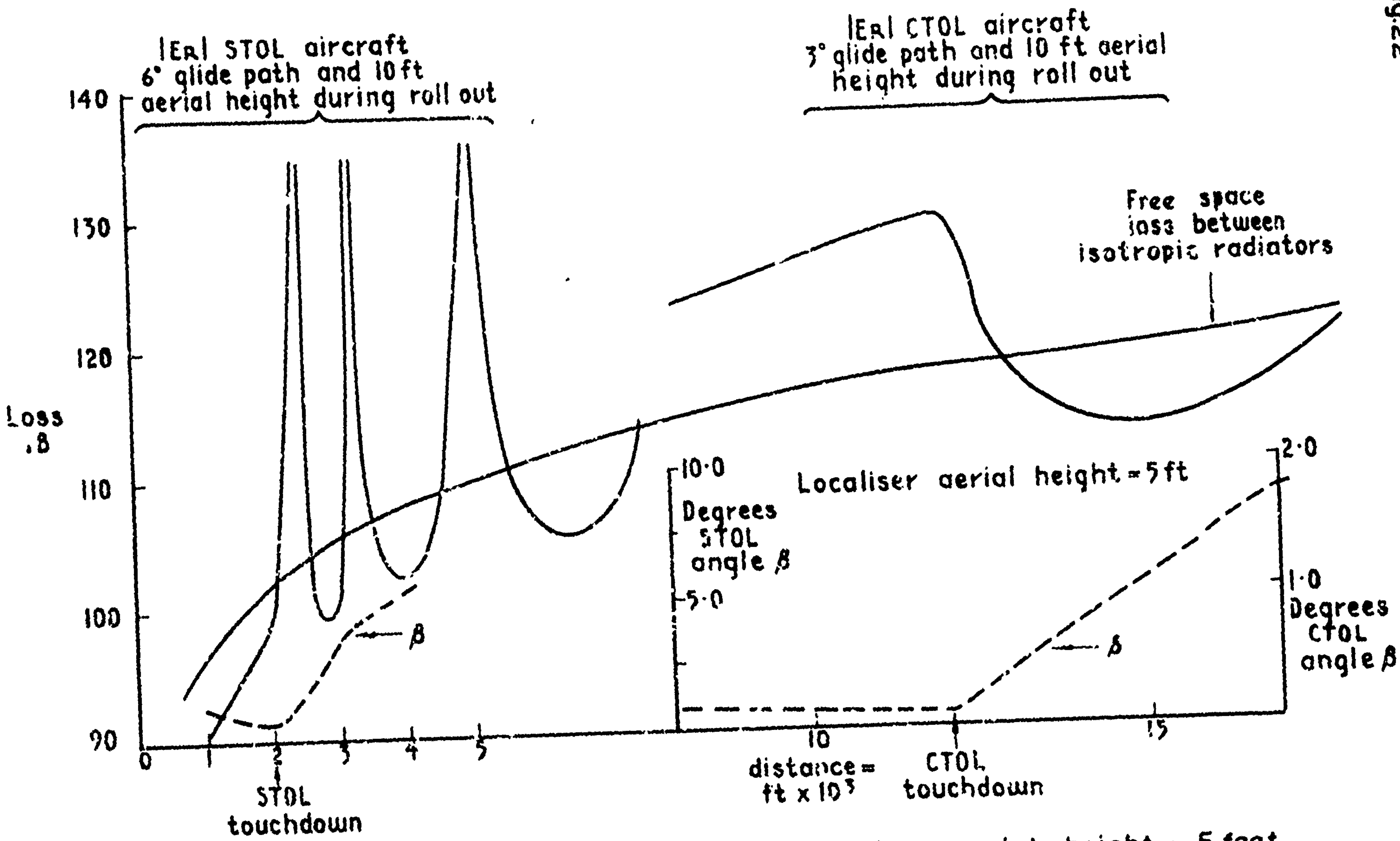

Fig.22 STOL and CTOL fading patterns localiser aerial height – 5 feet

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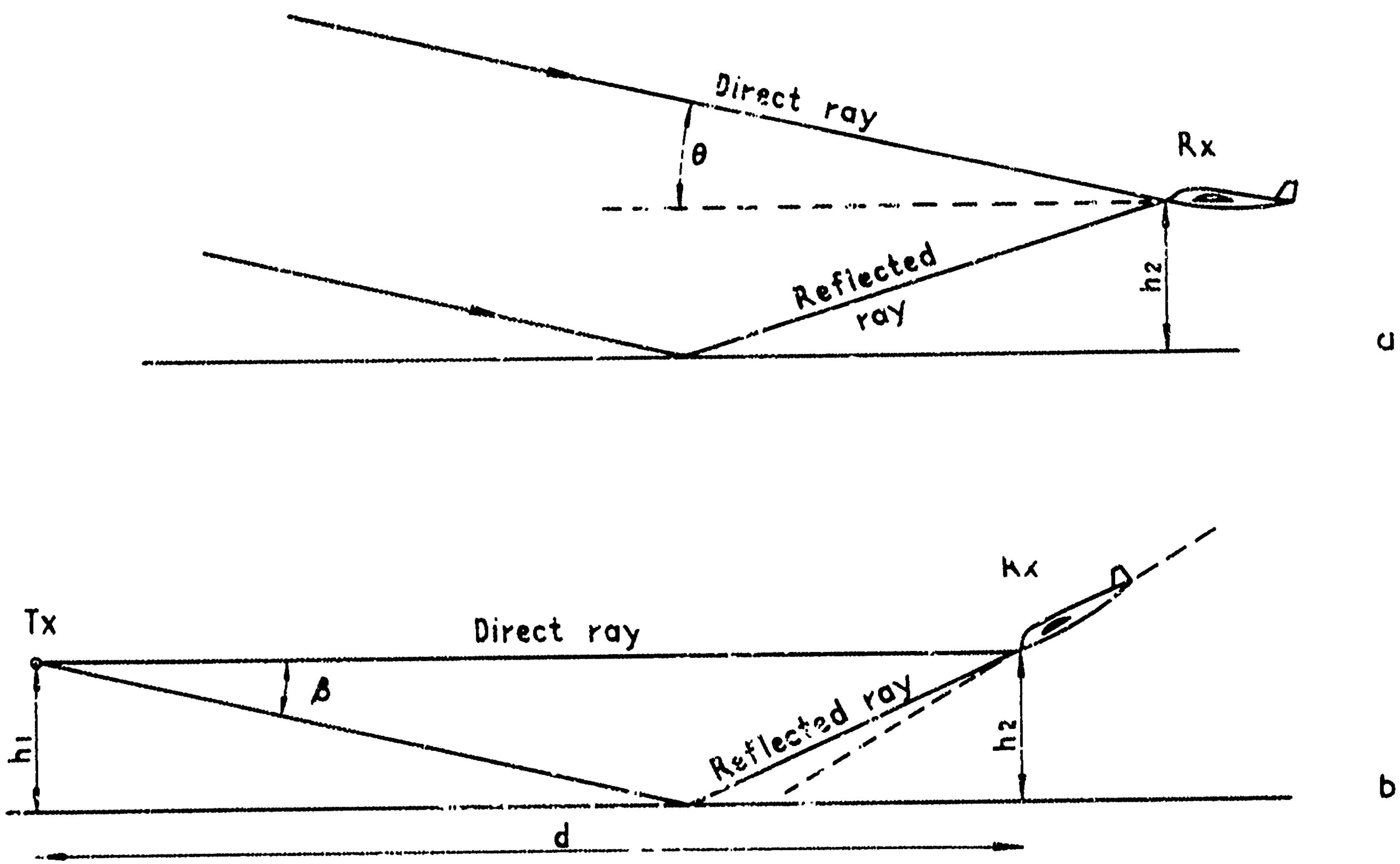


Fig.21 a & b Geometry of interference mechanisms

Fig.21 a&b

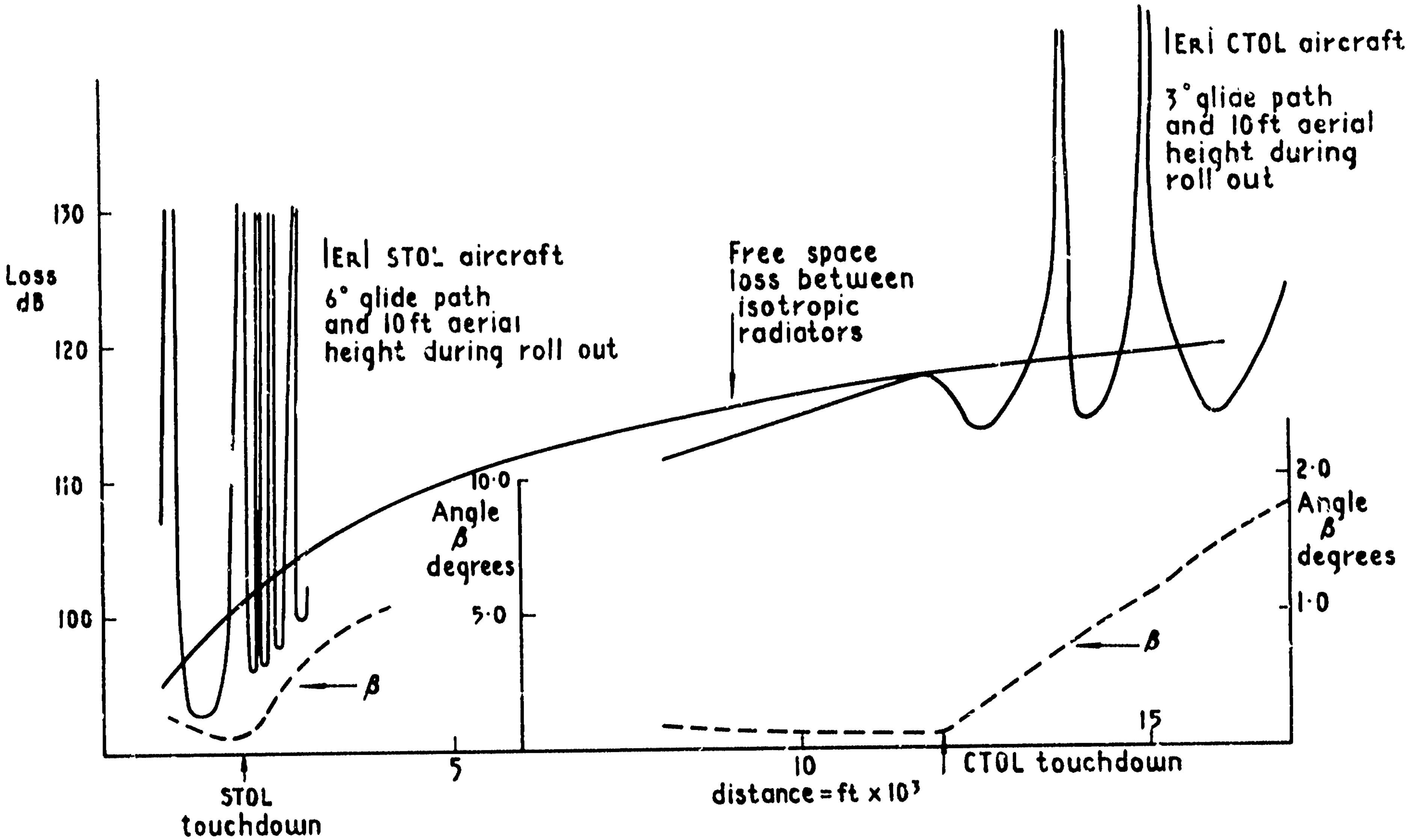


Fig.23 STOL and CTOL fading patterns localiser aerial height 20 ft

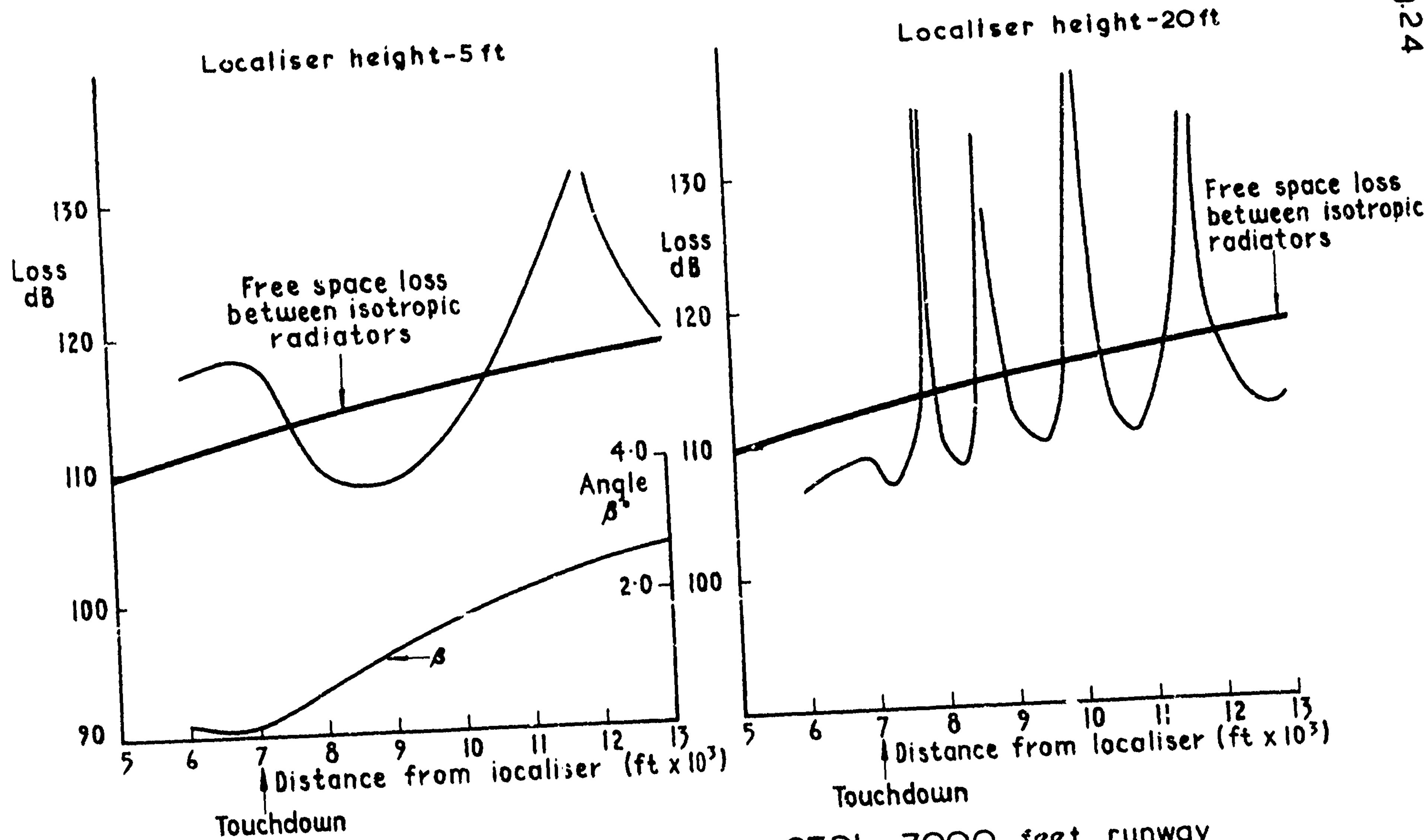


Fig. 24 Fading patterns for CTOL 7000 feet runway localiser aerial heights 5 and 20 feet

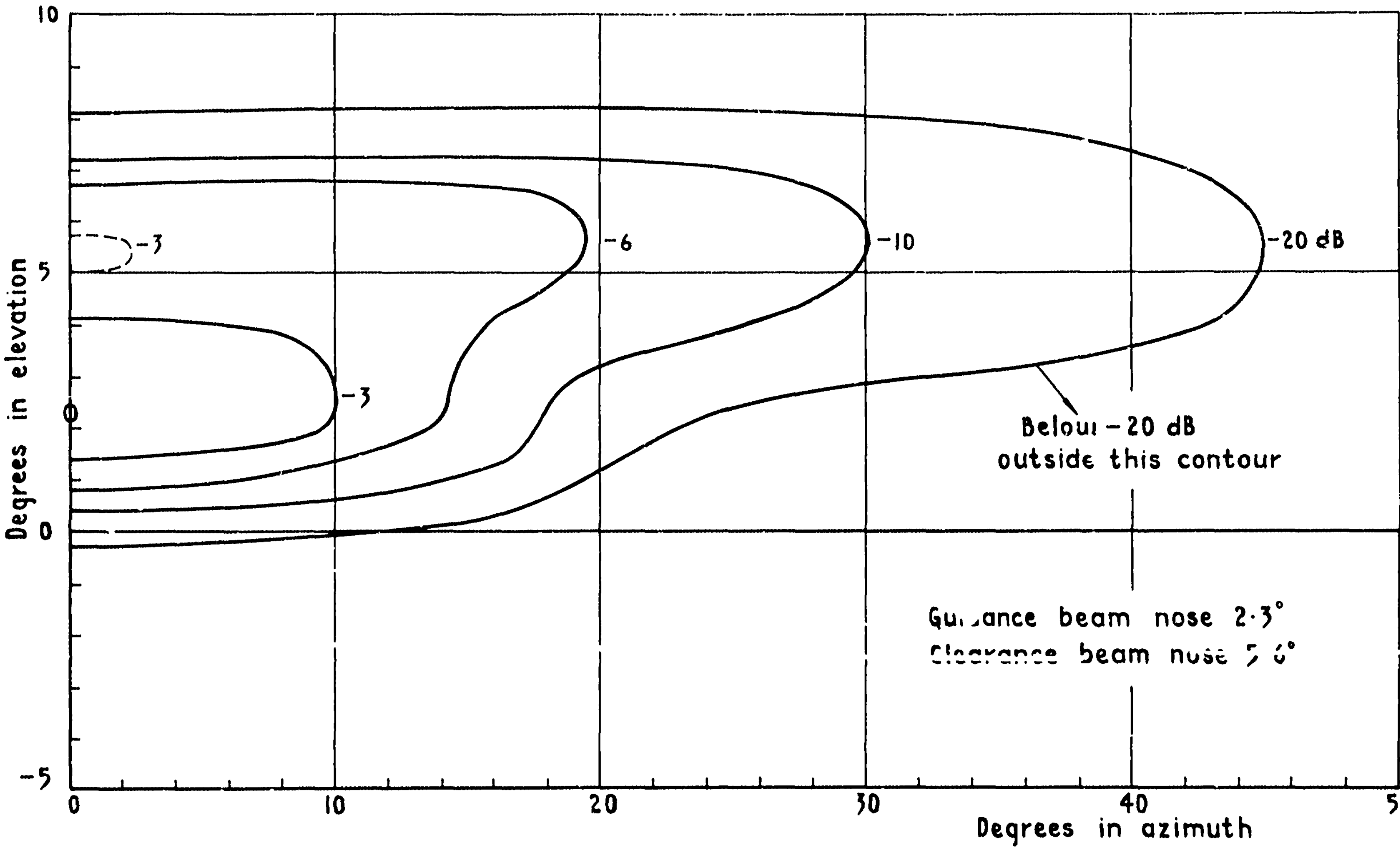
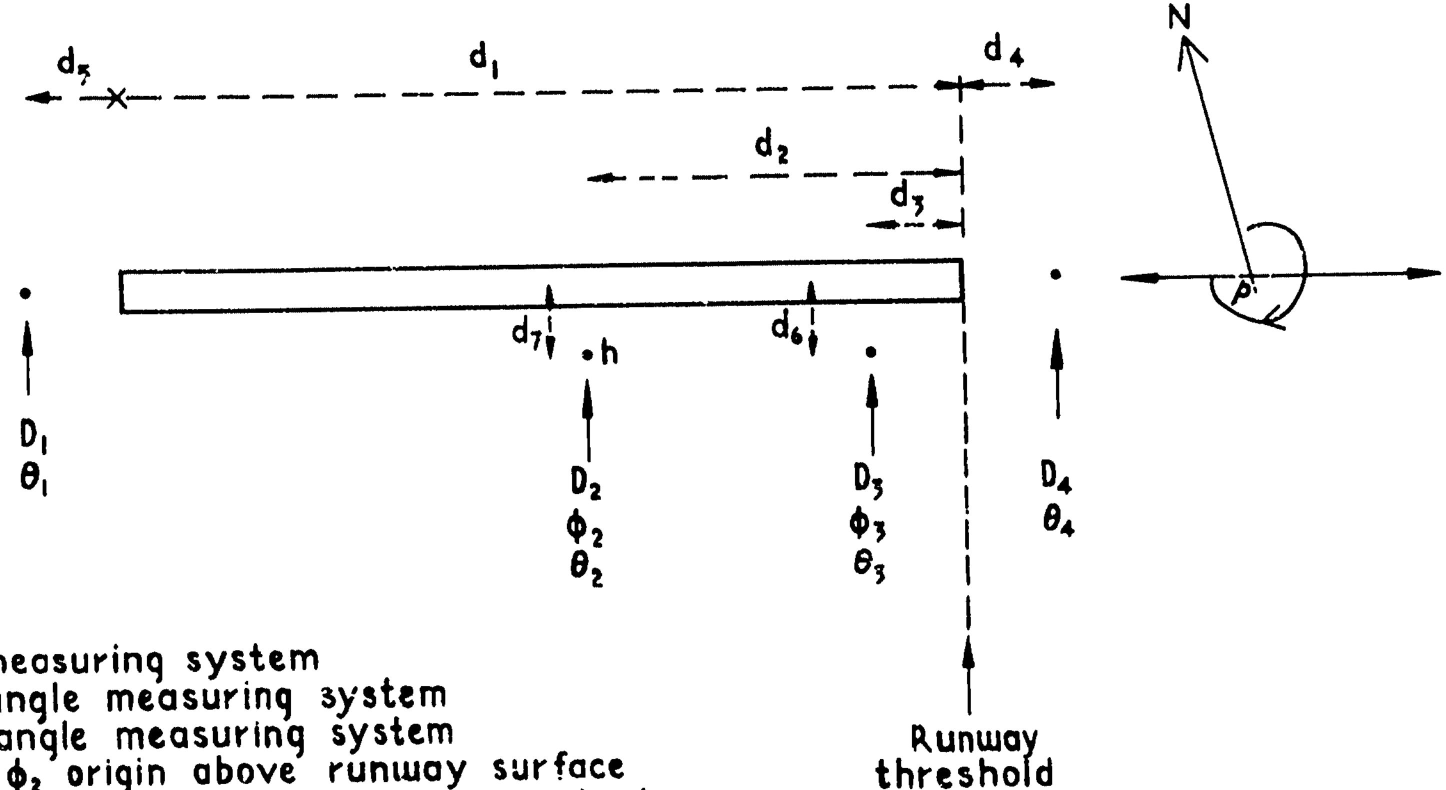


Fig.25 Localiser aerial contour pattern to minimise fading losses



D = Distance measuring system
θ = Azimuth angle measuring system
ϕ = Elevation angle measuring system
h = Height of ϕ_2 origin above runway surface
d_n = System position / runway distance constants
β = Runway heading
I = Runway ident

Fig.26 Ground system combinations

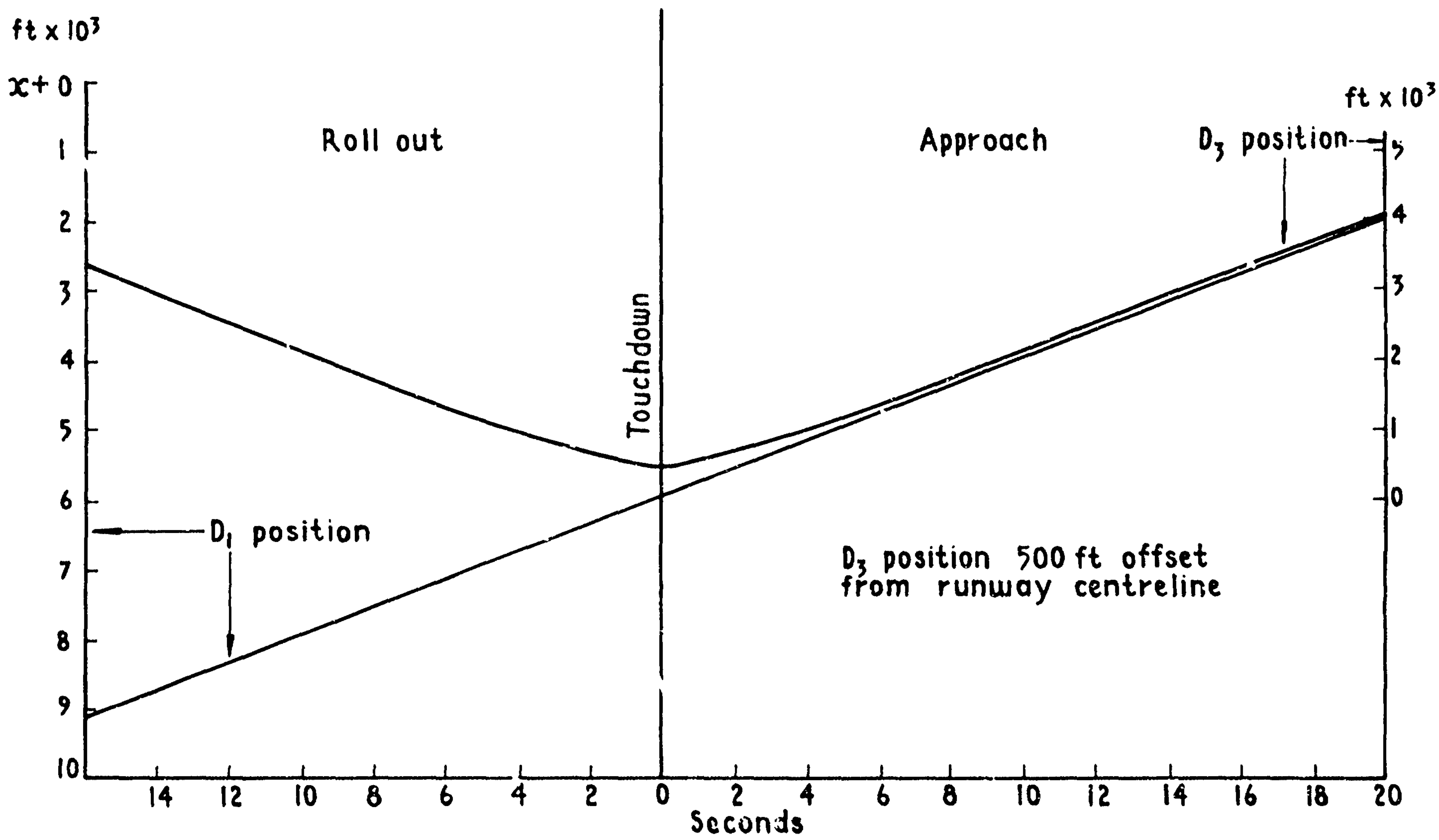


Fig.27 Distance functions for D_1 and D_3 positions

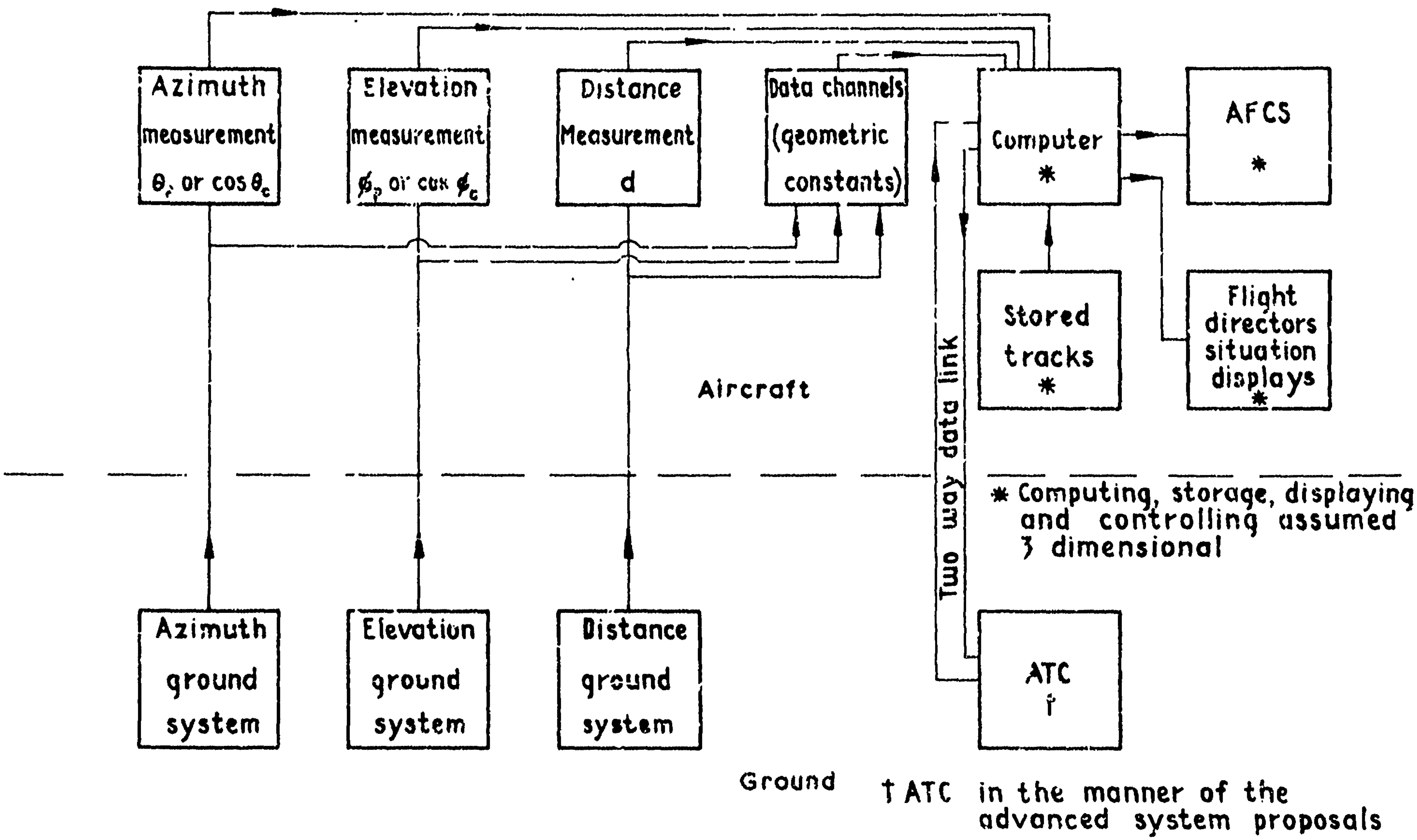


Fig.28 The air/ground system

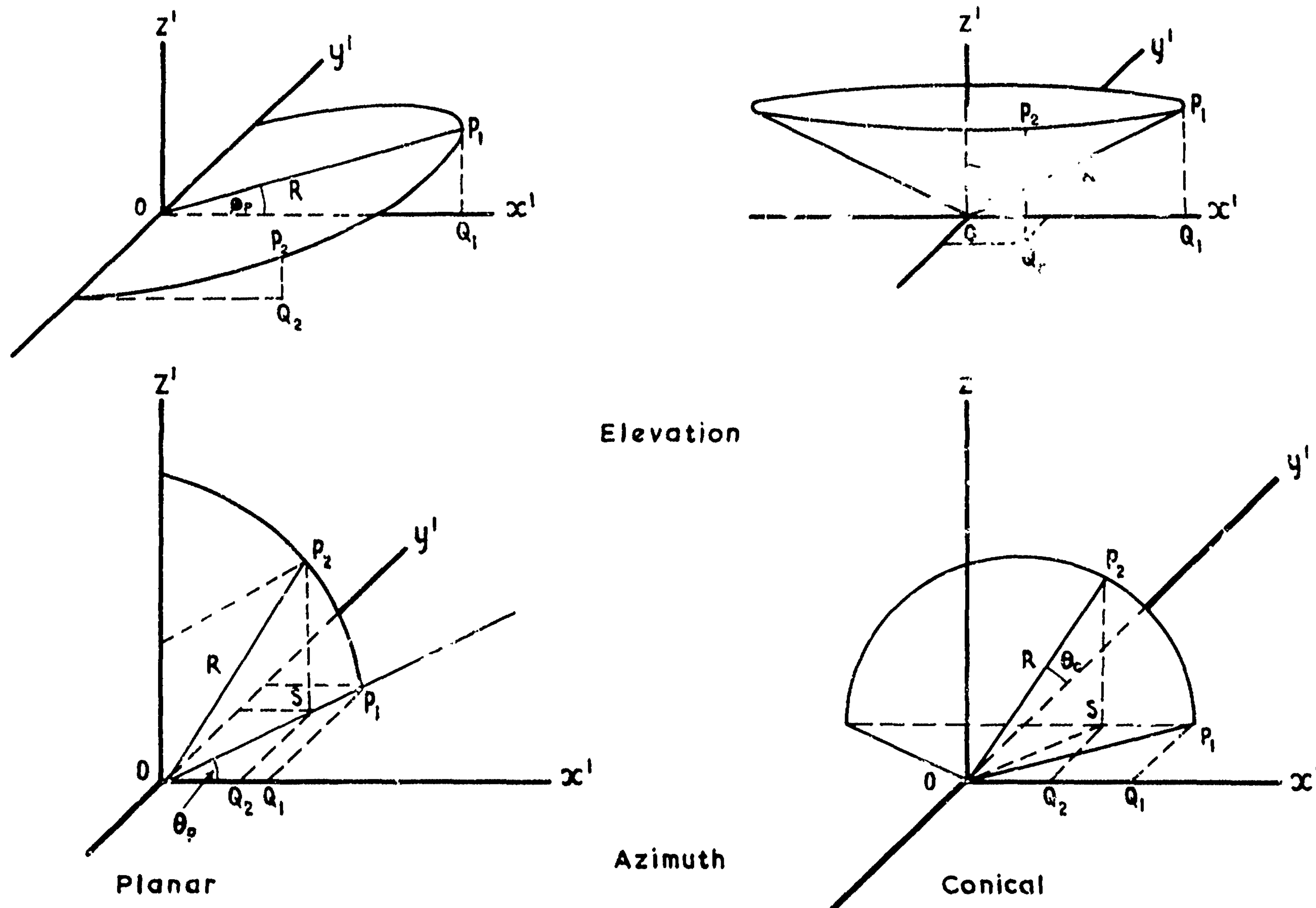


Fig.29 Planar / conical geometries

Fig.30

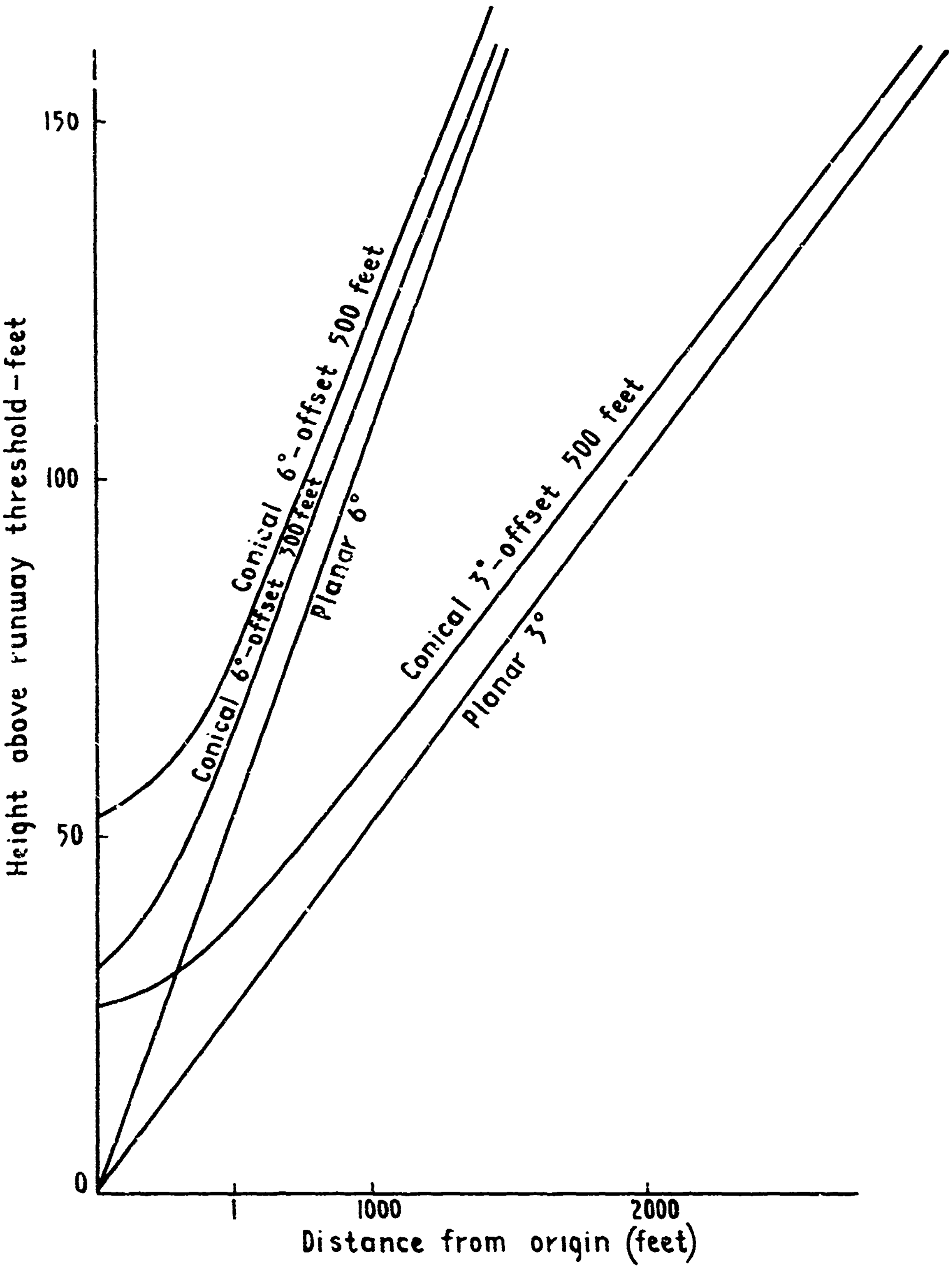


Fig.30 Planar / conical glide paths - common origin

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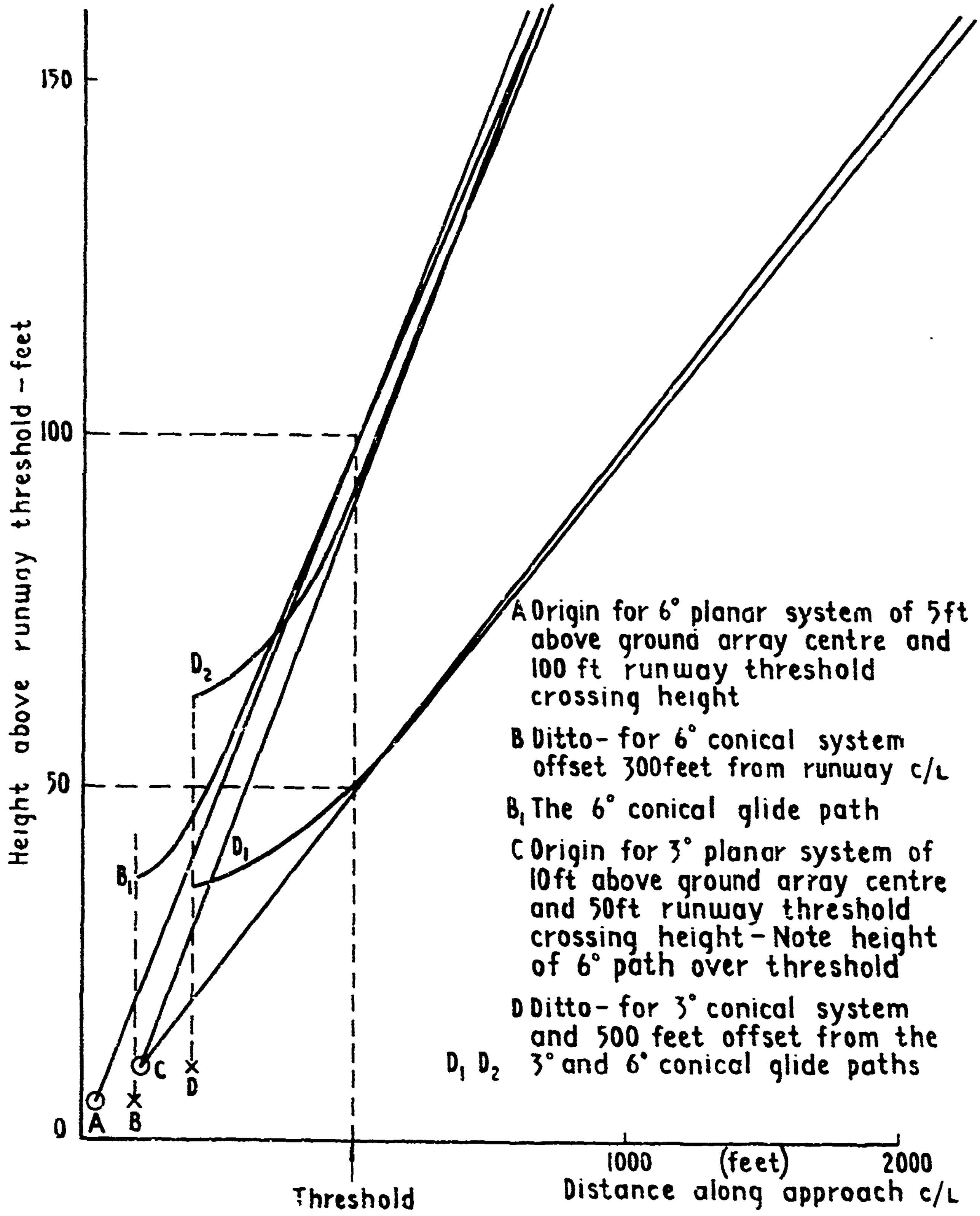

Fig.31 Planar/conical glide paths – optimised origins

Fig.32

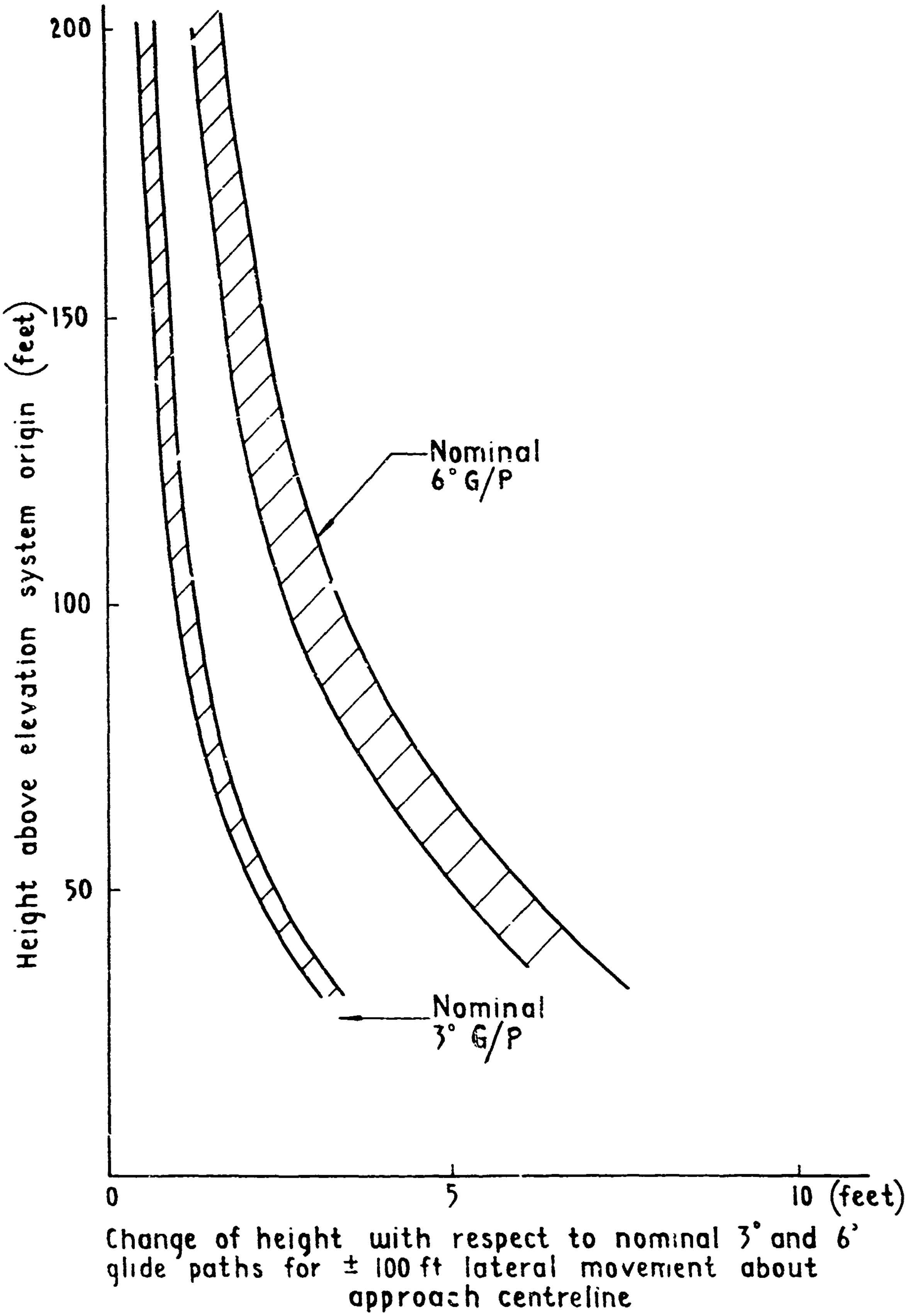

Fig.32 Conical G/P-azimuth/elevation cross coupling

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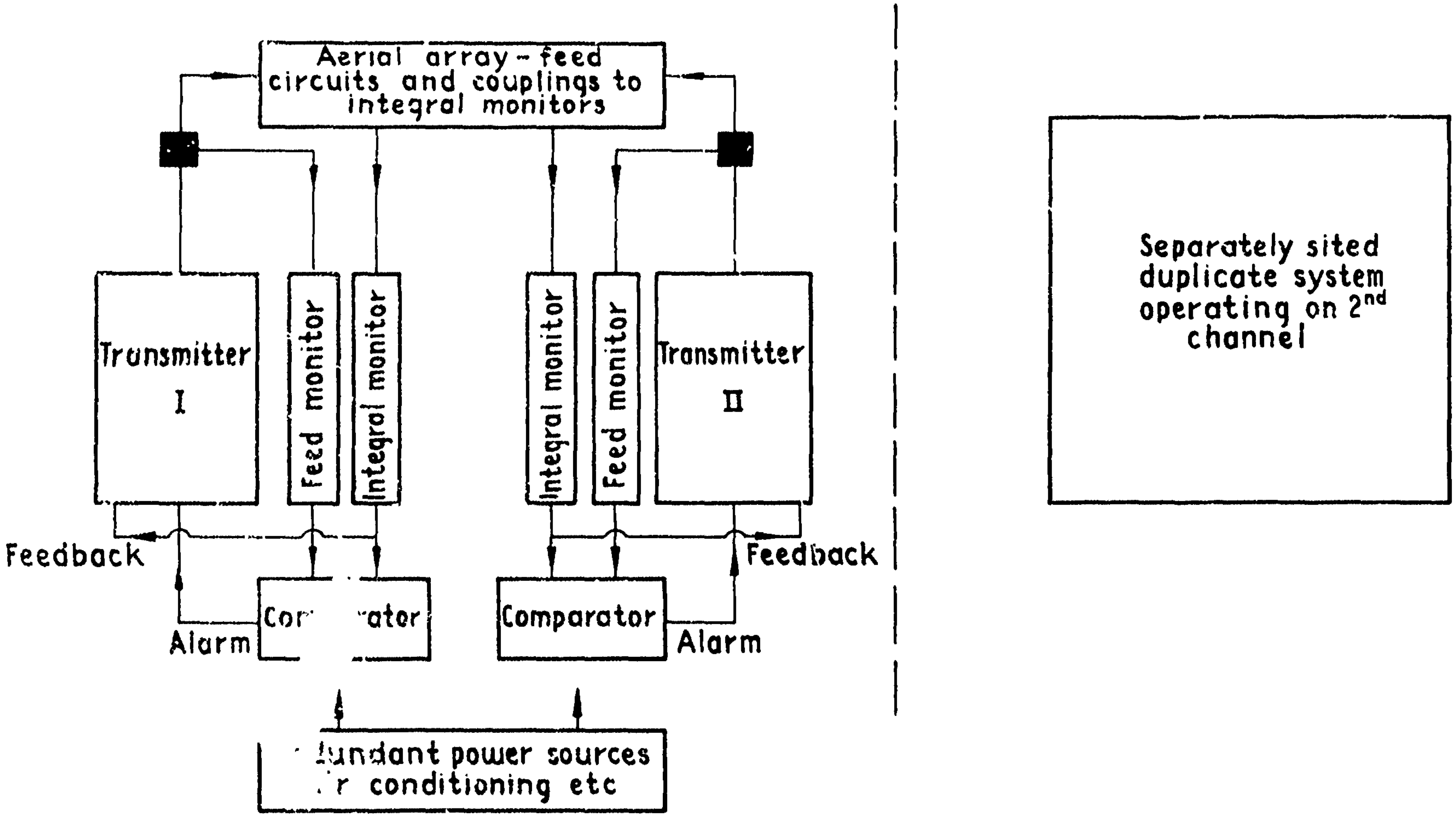

Fig.33 Duplicate-redundant ILS

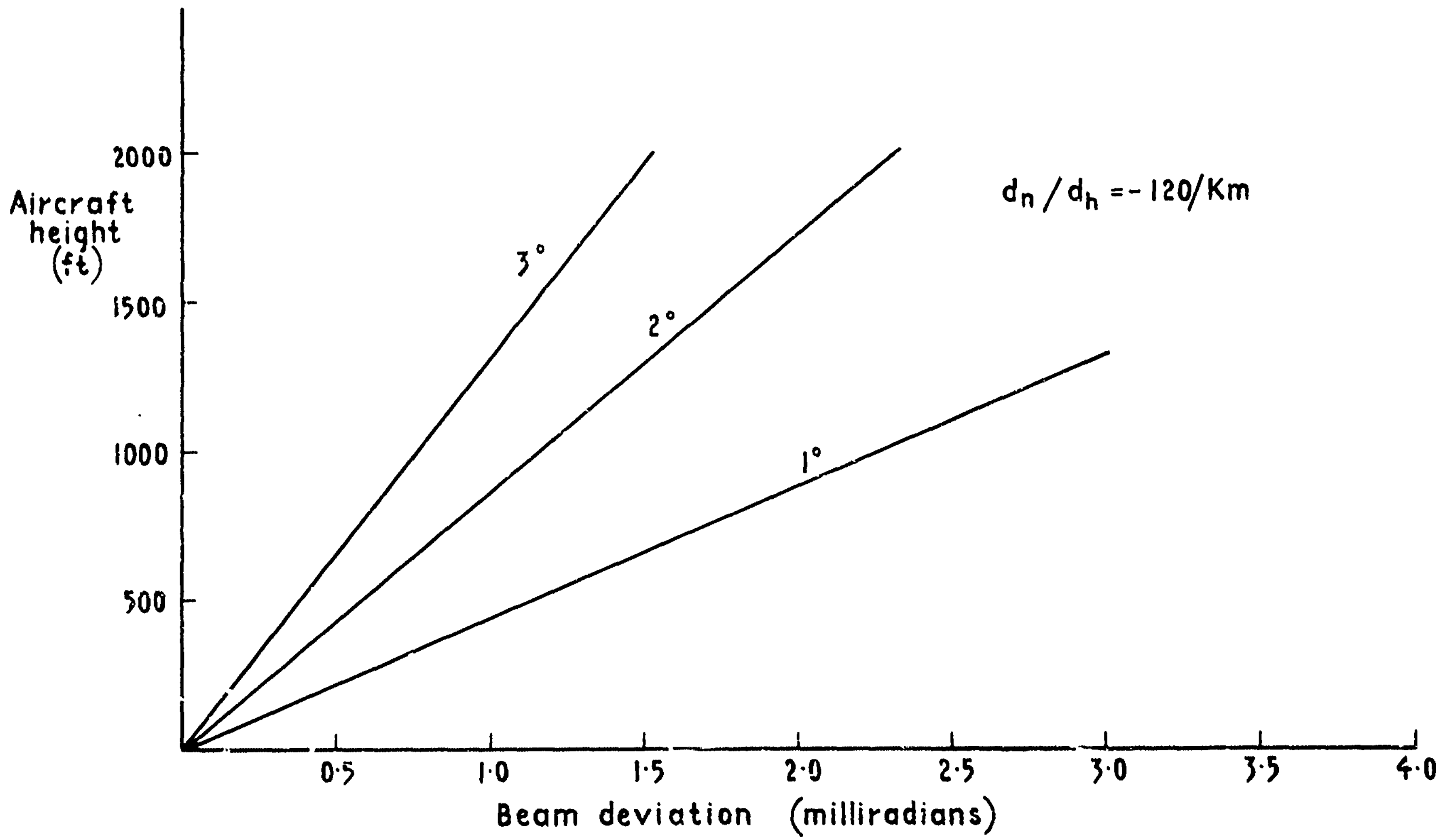

Fig.34 Elevation beam deviations due to refraction